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LEGIBILITY OF SELF-LUMINOUS DISPLAY VARIATIONS VIEWED THROUGH A--ETC(U)

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Technical Report

LEGIBILITY OF SELF-LUMINOUS DISPLAY VARIATIONS VIEWED THROUGH ARTIFICIALLY TURBID WATERS

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U.S. National Bureau of Standards

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Contract Number: N00014-74-C-0276
Work Unit Number: NR 196-134

Prepared for:

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research
Arlington, Virginia 22217

Prepared by:

OCEANAUTICS, Inc.

422 Sixth Street
Annapolis, Maryland 21403

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Two laboratory experiments were conducted into the problem of optimizing the characteristics of self-luminous displays for legibility in turbid water typical of Navy diving operations. The turbidity characteristics of coastal oceanic and harbor waters were simulated by artificial materials whose concentrations and physical diameters matched the median values of suspensoids in the two natural waters. Optical properties of the two artificially turbid waters were measured several times during the period of the experiments, and next page

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the 'Harbor' samples were compared to properties of samples taken from the Chesapeake Bay.

Experimental variations in the self-luminous digital display included size, luminance and wavelength; maximum legible viewing distance was used as the observer's response criterion. Both experiments used a repeated measures experimental design, each with ten observers recruited from diving elements of the U.S. Navy. Legibility of the display was significantly affected by the turbidity differences. Results suggest that displays, viewed through a facemask in turbid water by dark-adapted observers, need to be closer to the eyes, brighter, and larger than displays viewed in air; also the shorter wavelengths (blue/green) were more legible than the longer wavelengths (yellow/orange).

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Mr. Allan Slater of Emergency Care Research Institute, Plymouth Meeting, Pennsylvania, designed the test tank and optical system, and made many valuable contributions to the research design.

Dr. Kent Boyd of the National Institute of Advanced Studies, Washington, D.C., made important contributions to the experimental design and data collection procedure. He developed and implemented computer programs for the variance analyses made of the legibility data.

LEGIBILITY OF SELF-LUMINOUS DISPLAY VARIATIONS VIEWED THROUGH ARTIFICIALLY TURBID WATERS

I. INTRODUCTION

Divers are required to read visual displays in dark and turbid waters, but the displays are not designed to account for the particular optical and perceptual effects characteristic of this unusual viewing environment. A substantial research literature has developed in the area of display design for in-air applications (for summary reviews see Ketchel and Jenny, 1968; Meister and Sullivan, 1969; Grether and Baker, 1972; Carel, et al, 1974) and on the effects of underwater environments on basic visual processes such as acuity, depth perception, size and distance estimation (see Kent and Weissman, 1966; Kinney, et al, 1968 and 1970; Luria, 1968; Luria, et al, 1967 and 1972). Minimal effort, however, has been directed specifically to the problem of optimizing displays for underwater applications. Poock, 1972a and 1972b, has studied the effects of color and viewing distance variations using a waterproofed voltmeter display viewed through water of varying degrees of opaqueness. The scattering effects of naturally turbid waters were not included in these studies, however, since a black dye and not suspended particles was used to simulate turbidity.

The simulation of natural water turbidity, i.e., particles suspended in the water, is critical to the conduct of research on underwater displays. The particles have two important impacts on light transmission: first, the particles cause forward scattering of light in the pathway between the display and the observer's eyes; and, second, the particles dissipate light energy by scattering in all directions. The consequence of forward scattering is to reduce brightness contrast between the display and the background, thereby reducing legibility of the display; the consequence of the second effect is to

selectively reduce light energy according to its wavelength. Very small particles, for example, selectively scatter light in the shorter (blue) wavelength area of the visible spectrum relative to the longer (red) wavelengths, thereby reducing the visibility of blue light. This scattering phenomenon contrasts with the absorption of light energy by non-turbid water which is selective according to wavelength in the opposite direction, i.e., the longer wavelengths (red) are absorbed more quickly (over a shorter transmission pathway) than the shorter wavelengths (James and Birge, 1938). The optical effects of light transmission in turbid water in turn affect perception underwater; for example, the visibility of variously colored objects is a function of the specific turbidity condition; and size/distance perceptions in turbid water are different than in clear water (Kinney, et al, 1967 and 1969).

Laboratory research on display legibility in turbid waters is made difficult by the instability of natural water when removed from its original location. Living organisms tend to either grow or die, suspended materials tend to flocculate and settle out; a constant viewing medium is impractical to maintain over the time required for a typical experimental effort. Because of its importance as an environmental factor in display legibility, the simulation of natural water turbidity by artificial means was a priority objective of the present research. Guidelines for the selection of turbidity conditions to be simulated were derived from an analysis of environmental determinants of display legibility (Vaughan and Williams, 1976). This analysis identified 'Harbor' and 'Ocean' categories as typifying the range of operational waters of concern to Navy divers. These two categories are comparable to Jerlov's (1968) Type 9 and Type 5, and to Navy designations of 'inshore' and 'nearshore' waters. The physical characteristics of 'Harbor' turbidity to be simulated were based on data reported by Schubel, 1969 and 1971; and by Schubel, et al, 1970, who measured the sizes and concentrations of particles suspended in samples of water taken from Chesapeake Bay. The physical characteristics

of 'Ocean' turbidity to be simulated were based on the work of Sheldon, et al, 1972, who took similar measurements in oceanic waters. As an initial effort in the physical simulation of these two viewing environments, the median size of suspended particles was selected as the turbidity simulation objective: 1 micrometer diameter particles for 'Harbor' and 25 micrometer diameter particles for 'Ocean'.

Since the turbidity environments of oceans and harbors are known to be physically and optically dissimilar, different perceptual effects were anticipated in the two simulated environments; consequently, two experiments were carried out. In the first, display variations were assessed for legibility in two concentrations of 'Harbor' turbidity; in the second experiment, display variations were assessed in two concentrations of the 'Ocean' turbidity environment.

Selection of the visual task to be performed, the type of display format and the characteristics of the display to be included in the two experiments were based on a requirements analysis (Vaughan and Williams, 1976). The effect of the requirements analysis was to focus the experiments on quantitative reading as the most common visual task, and on transilluminated or self-luminous display formats as the preferred means of display support for this task. Display size, luminance, wavelength and viewing distance were identified as the main determinants of legibility. As contrasted with design guides for in-air applications, the requirements analysis suggested that underwater displays would need to be larger, less luminous and viewed at shorter eye-to-console distances. The analysis of wavelength suggested three alternative optimization possibilities: a 555 nanometer peak wavelength to optimize cone-mediated vision, a 505 nanometer wavelength to optimize rod-mediated vision and 585 nanometer or longer wavelength to best match the physical transmissivity characteristics of the turbid medium.

The two experiments were designed to provide more concrete design guides for underwater display applications. Table 1 presents the several variables included in the experiments.

Table 1. Organization of Variables Included in Experiments

Observer Characteristics	Type of Visual Task	Turbidity Characteristics of the Water	Display Type and Characteristics
Normal Color Vision 20/20 Near Acuity Dark-Adapted Accommodation Near-Point	Quantitative Reading	'Harbor' simulation by 1 micrometer diameter particles 'Ocean' simulation by 25 micrometer diameter particles Concentrations of particles at 10 and 30 parts per million	Self-luminous digital display Size Luminance Wavelength Viewing Distance

II. METHOD

A. Turbid Water Simulation

The physical characteristics of two categories of natural water were simulated: 'Harbor' water turbidity was defined by concentrations of 1 micrometer diameter particles; 'Ocean' turbidity was defined by concentrations of 25 micrometer diameter particles. Latex spheres were used to represent naturally occurring suspensoids. The 'Harbor' turbidity was simulated by polystyrene spheres having a mean diameter of 1.101 micrometers and standard deviation of .0055 micrometer. The 'Ocean' turbidity was simulated by styrene divinylbenzene spheres of 25.7 micrometers mean diameter and a 10.1 micrometers standard deviation. These spheres are prepared by either emulsion or suspension polymerization techniques by the Dow Chemical Company for a variety of scientific applications such as the calibration of electron microscopes. In addition to their availability in a range of sizes, the latex spheres compare favorably with natural silts and clays in their index of refraction, 1.59 vs 1.53. Unlike natural materials they are white in color, uniformly spherical in shape, and less dense, 1.05 grams per cm^3 as compared to 2.65 grams per cm^3 characteristic of clays and silts. As materials for simulating natural turbidity, however, they have several advantageous characteristics: they are sterile, do not flocculate, and have very low settling rates. These characteristics suggest that a constant viewing medium can be maintained over time, that the subjects tested on the last day will encounter environmental conditions acceptably similar to the first.

The amount of particles in suspension in natural water is defined as total suspended load and expressed as a ratio of weight of material to weight of water; usually milligrams of suspended material per kilogram of water. Since there are a million milligrams in a kilogram, total suspended load is described

as parts per million. In order to simulate 10 and 30 parts per million sediment loads of natural waters, the difference in the densities of natural and artificial materials had to be accounted for. Since the density of latex spheres is 1.05 grams per cm^3 while the density of clay particles is about 2.65 grams per cm^3, more latex spherical particles would be present in a given suspended load than clay particles. Consequently, in order to obtain the same number of individual particles in an artificially turbid sample, the value of grams of suspended material was decreased by the ratio of the density of latex to that of clay. For example, to optically simulate with latex particles a sediment load of ten parts per million, the sediment load of 10 was divided by the aforementioned ratio ($2.65 \div 1.05 = 2.52$) resulting in an equivalent suspended load of 3.97 parts per million. In this manner a suspended load of 3.97 parts per million of latex particles will contain the same number of individual light scatterers as a load of 10 parts per million of suspended sediment; 11.90 parts per million will be the latex equivalent of 30 parts per million of natural sediment.

Particle loads of 10 and 30 parts per million have substantially different meaning in the two natural environments as well as in the 'Harbor' vs 'Ocean' simulations since the number of individual scatterers present in each gram of suspended material varies markedly with the particle size. Since the mass of each particle is directly related to its volume and the volume is directly related to the cube of the diameter, any small increase in particle diameter will result in a large increase in the mass of any given particle. Suppose, for example, we calculate the number of particles present in a load of one part per million if the diameter of each particle is assumed to be one micrometer (10^{-4} cm). Using the formula for total suspended load in milligrams per kilogram (L) and solving for the number of particles per cm^3(N):

$$L = 1.33\pi R^3 dN \times 10^6$$

or

$$N = \frac{L \times 10^{-6}}{1.33\pi R^3 d}$$

where:

R = particle radius in cm

d = particle density in gms per cm^3

10^6 = multiplying factor so that L can be expressed in parts per million (mg/kg) rather than parts per part (g/g)

Letting R be 0.5×10^{-4} cm, L = 1 ppm, and d = 2.65g/cm^3 N works out to be 7.2×10^5 particles per cm^3 for every part per million of suspended load. In other words, if the load were 10 parts per million, there would be 7.2 million particles in every cubic centimeter (milliliter) of water. A load of 30 parts per million would have three times as much or 21.6 million particles in every cubic centimeter of water. Thus, it may be seen that when the load of these very small particles is increased from 10 to 30 parts per million, 14.4 million particles are added to every cubic centimeter of water.

On the other hand, if we let R be 2.5×10^{-4} cm (25 micrometer diameter) with d still the density of naturally occurring silts and clays (d = 2.65), we find that N works out to be 46.4 particles per cubic centimeter for every part per million of suspended load. A load of 10 parts per million of 25 micrometer particles would contain 464 particles per cubic centimeter of water, while a load of 30 parts per million of these larger particles would contain 1,392 individual scatterers in each cubic centimeter. In this case increasing the load from 10 to 30 parts per million would add 928 particles per cm^3 as compared to 14,400,000 particles in the case of the 1 micrometer diameter particles. The magnitude of the differences in numbers of particles (i.e., individual light scatterers) per cubic centimeter of Harbor vs Ocean water can be seen from Table 2.

Table 2. Theoretically Determined Number of Particles per Milliliter of Water Defining 10 and 30 Parts per Million Suspended Load for 'Harbor' and 'Ocean' Turbidity Conditions

Turbidity Condition	Suspended Load	
	10 ppm	30 ppm
'Harbor' (1 micrometer diameter particles)	7.2×10^6	2.16×10^7
'Ocean' (25 micrometer diameter particles)	4.64×10^2	1.39×10^3

B. Display Variables

The experiments were directed to the legibility requirements of self-luminous, numeric displays. This general category includes a variety of display generation techniques; light emitting diodes (LED), electroluminescent films (EL), transilluminated panel cutouts, and electronically-generated displays. The element used to represent this general class was a 7-segment incandescent filament bar display, Pinlite DIP 640, manufactured by Refac Electronics, Inc. Three of these units constituted the basic display stimulus as shown in Figure 1. The basic, unfiltered display had a color temperature of 1700° Kelvin and an average filament luminance of 1800 ft-L as measured by a Spectra Pritchard Photometer Model 1980 using a 2 arc-minute spot centered on a single filament bar. Experimental variations in wavelength, luminance and size were generated by optically modifying this basic display.

1. Wavelength

Wavelength of the light emitted by the experimental display was varied in order to assess the effect on legible viewing distance. Wavelength is typically varied as a means of producing perceptions of color, but in the present experiments, display luminances required for legibility in the dark by dark-adapted observers were often below the threshold of cone-mediated

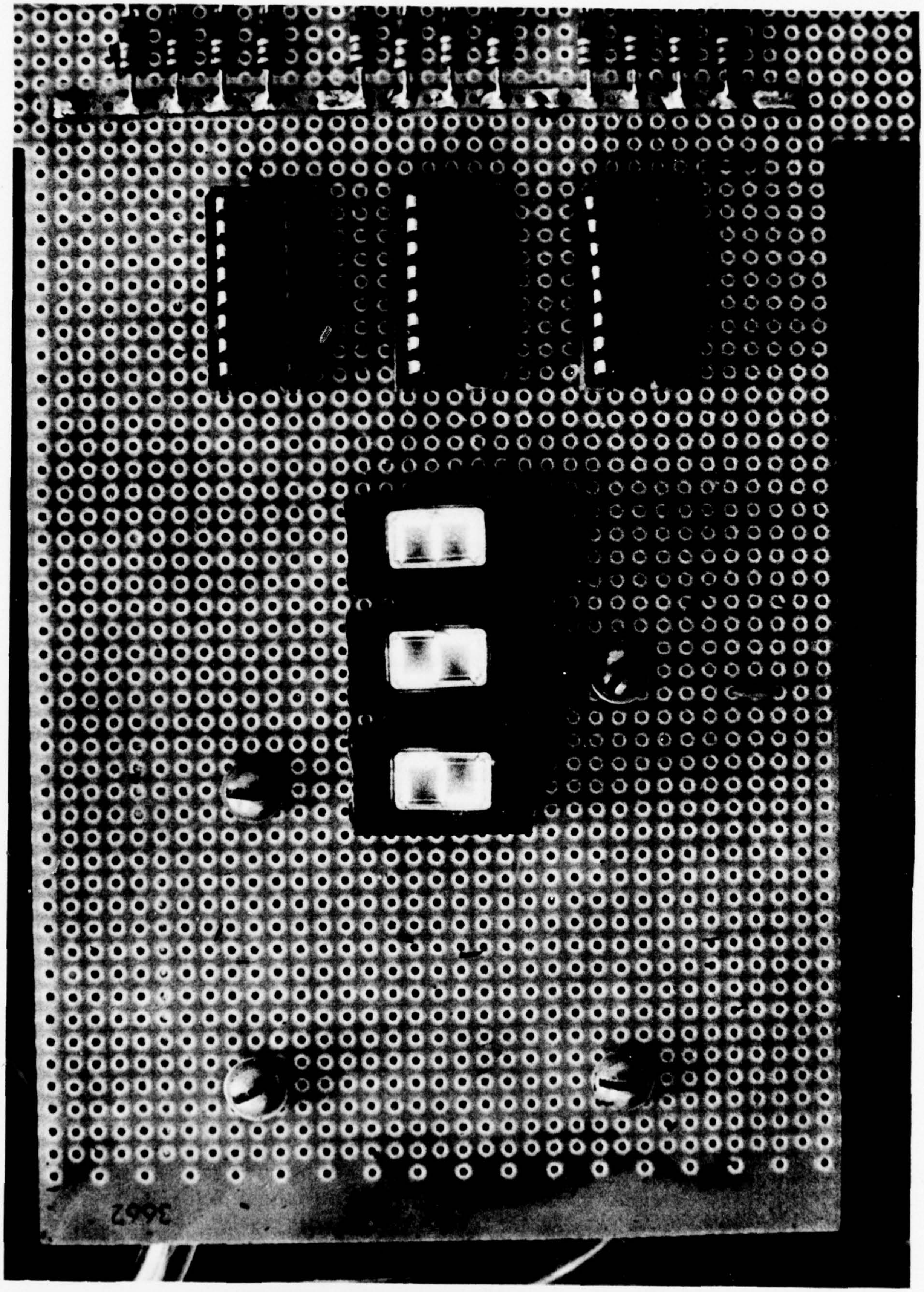


Figure 1. Basic 3-Digit Display Used in Experiments

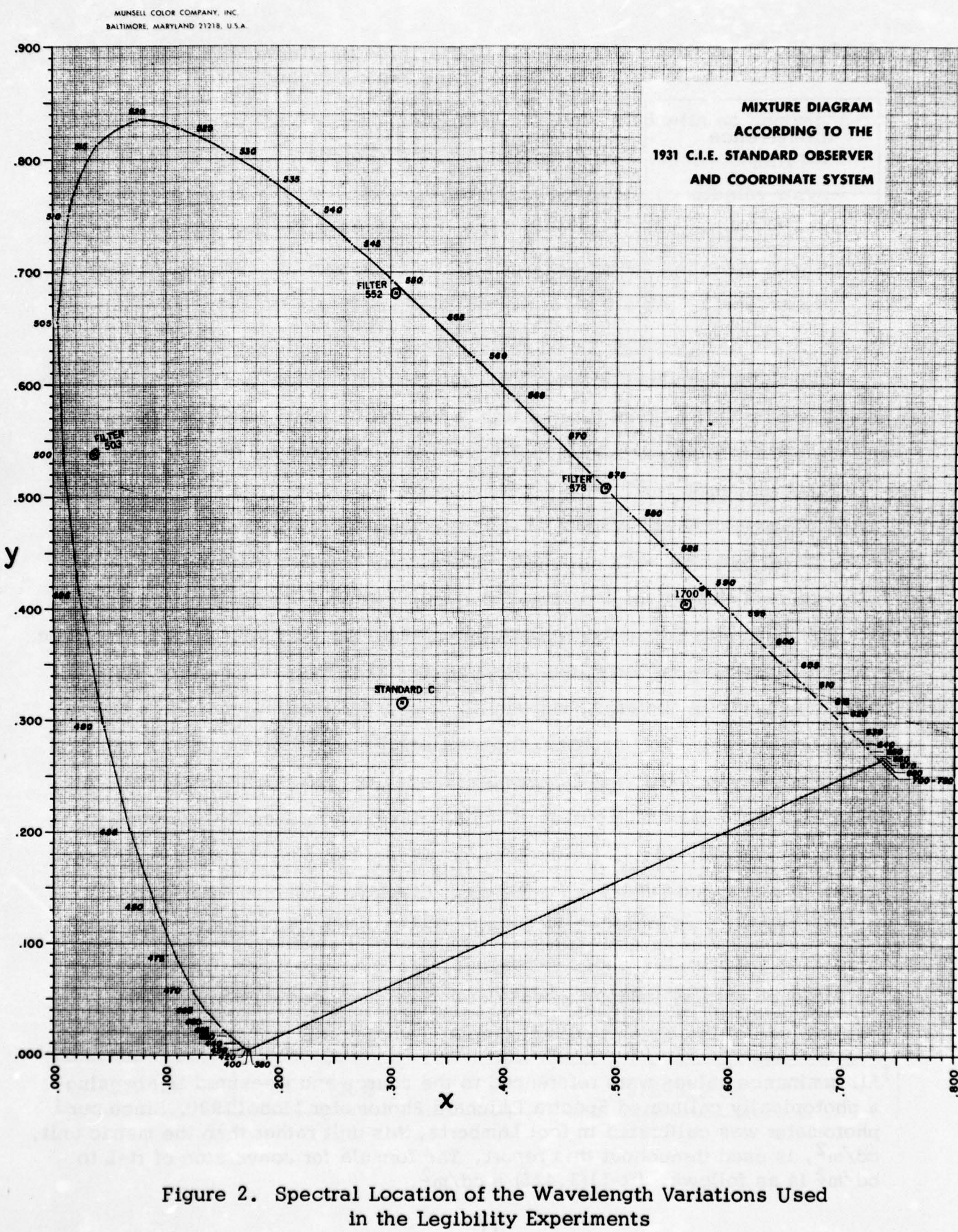


Figure 2. Spectral Location of the Wavelength Variations Used in the Legibility Experiments

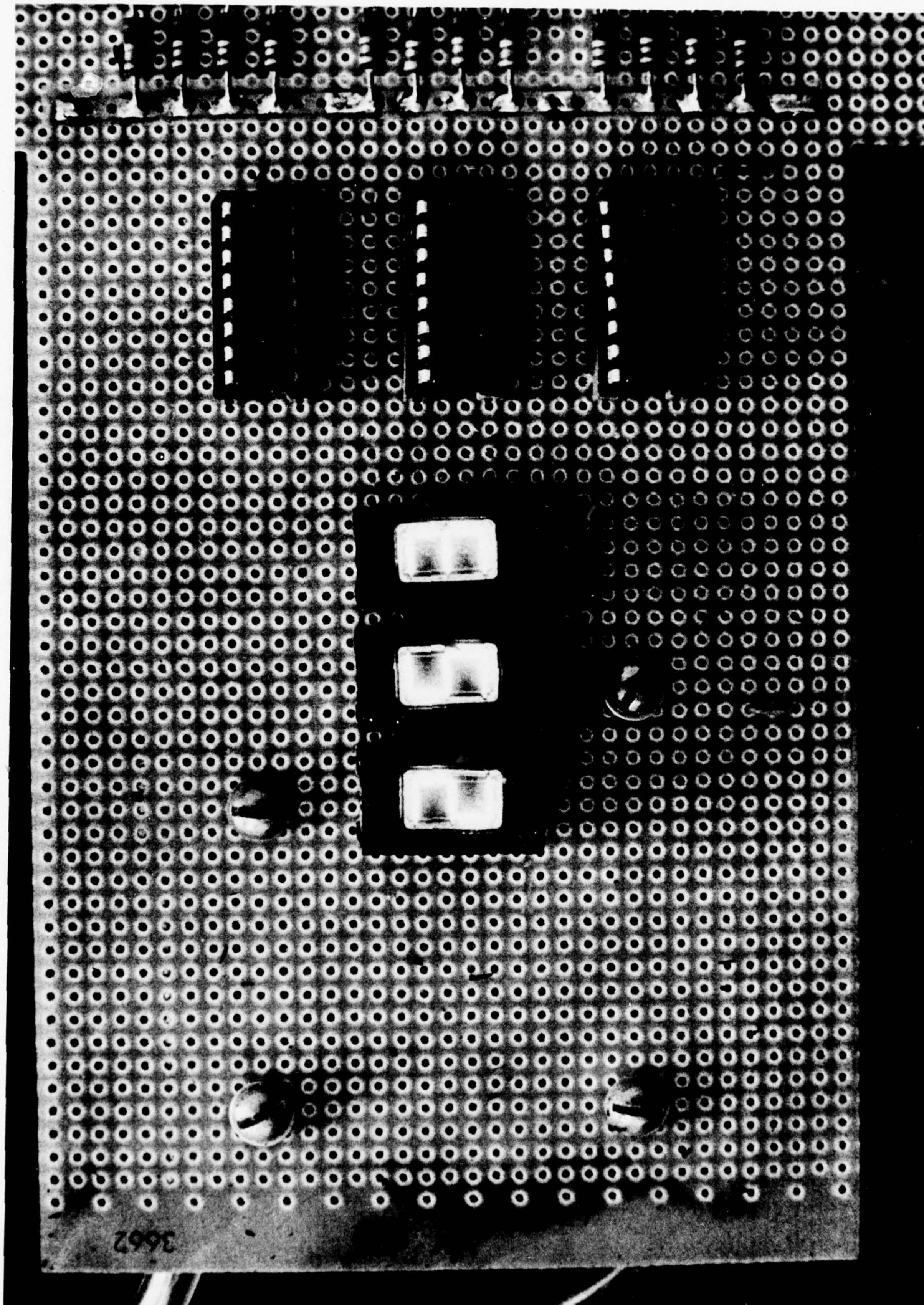


Figure 1. Basic 3-Digit Display Used in Experiments

vision; therefore, the 3-digit display was typically read with no accompanying perception of color. Wavelength was expected to be a significant factor in legibility according to one of three competing hypotheses: display wavelength could be optimized for legibility based on rod sensitivity, cone sensitivity or physical transmissivity through the turbid medium. Displays at wavelength 505 nm are optimal for rod-mediated vision, at wavelength 555 nm for cone-mediated vision, and at the longer wavelengths 580 - 640 nm for transmissivity through small-diameter particle turbidity as represented by the 'Harbor' simulations.

Experimental wavelengths were controlled by means of three narrow-band interference filters manufactured by Bausch and Lomb, Inc., whose transmission characteristics were close to the theoretical optima at 503 nm, 552 nm and 579 nm. Table 3 presents the main characteristics of the three filters. In addition, the unfiltered display was at a relatively low color temperature of 1700°K and approximated a dominant wavelength at 590 nm.

The tristimulus values and chromaticity coefficients for the three interference filters were computed (see Appendix B) and plotted on a 1931 CIE chromaticity diagram. Table 4 presents the chromaticity coefficients and Figure 2 locates the three filters and the raw display on the chromaticity diagram.

Table 3. Transmission Characteristics of the Interference Filters

Peak Wavelength	Percent Transmission at Peak Wavelength	Half-Band Pass (Bandwidth at 50% Transmission)
503 nm	43%	498-508 nm
552 nm	35%	548-556 nm
579 nm	38%	575-583 nm

Table 4. Chromaticity Coefficients of the Three Interference Filters Used to Modify the 'Color' of the Basic Display

Interference Filter	Chromaticity Coefficients		
	x	y	z
503 nm	.0350	.5382	.4268
552 nm	.3038	.6813	.0149
579 nm	.6085	.3900	.0013

At luminance levels adequate for cone vision, the raw display at 590 nm appeared orange, the 579 nm filtered light appeared yellow, the 552 nm green, and the 503 nm a greenish-blue.

2. Luminance[1]

Luminance was manipulated by placing combinations of neutral density glass filters over the basic display. Several 2 x 2-inch square neutral density filters of various nominal densities between 0.3 and 4.0 log units were obtained from Fish-Churman Corporation. Each filter was calibrated with each of the three interference filters and the manufacturer's nominal values adjusted to actual values. Appendix B contains a description of the calibration procedures and results. Given empirically determined densities of each filter, combinations could be specified which produced display luminances at half>log intervals between .001 ft-L and the maximum output of the display-interference filter combination, i.e., approximately 10 ft-L for the blue/green display, 30 ft-L for the green and yellow displays, and 1000 ft-L for the clear display. Luminance was varied in half-log intervals since brightness perception is generally regarded as a power function of the stimulus whose exponent is 1/3 to 1/2 (Stevens, 1975).

Although display luminance was defined by measurements from single filament bars of the seven-segment display, whole digit values were measured

[1]All luminance values were referenced to the source and measured in air using a photopically calibrated Spectra Pritchard Photometer Model 1980. Since our photometer was calibrated in foot Lamberts, this unit rather than the metric unit, cd/m^2, is used throughout this report. The formula for conversion of ft-L to cd/m^2 is as follows: $(\text{ft-L})(3.426) = cd/m^2$.

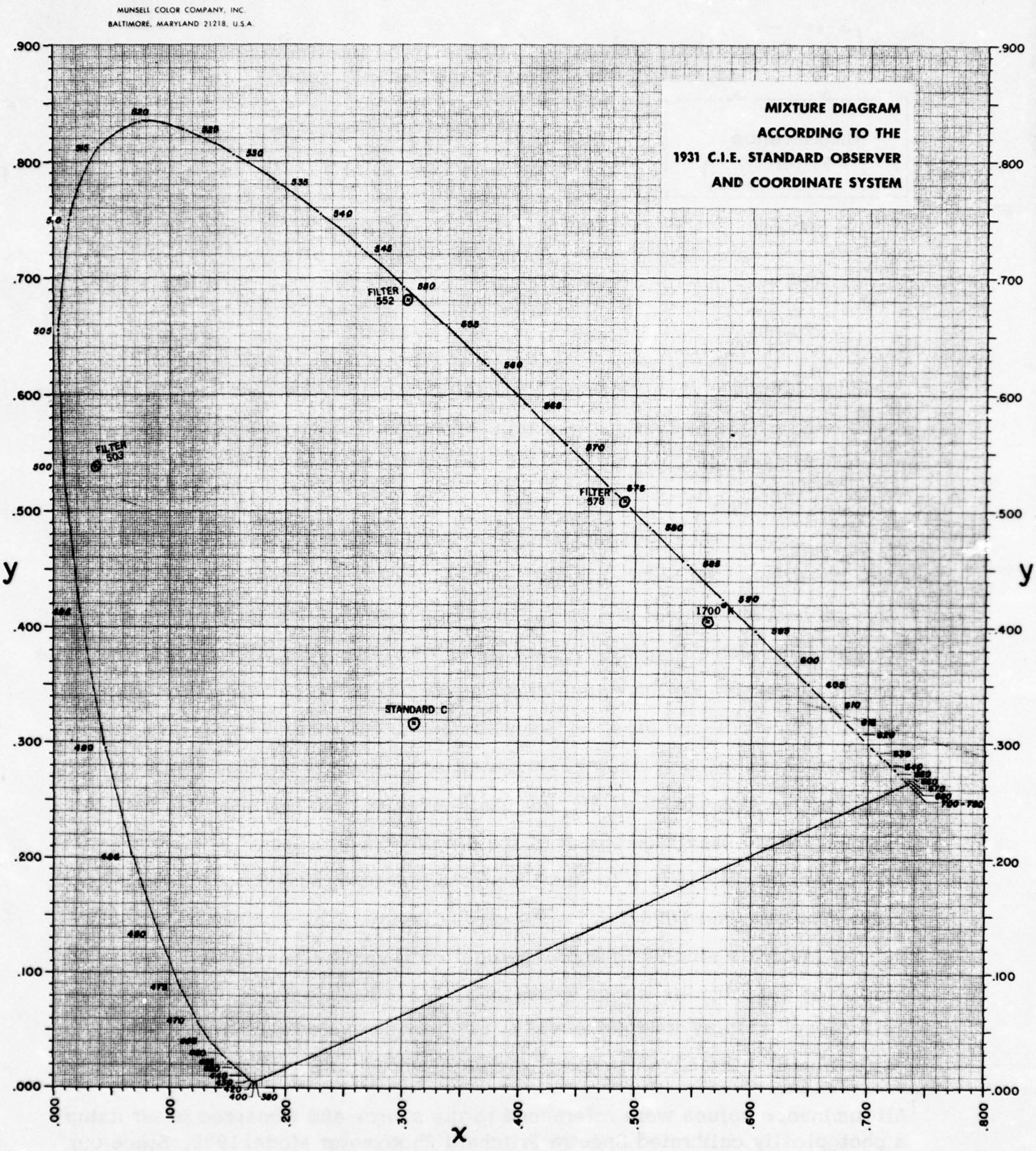


Figure 2. Spectral Location of the Wavelength Variations Used in the Legibility Experiments

using a 1° spot. Table 5 presents these whole-digit values of photopic luminance. Digits 0-9 are ordered in the table according to the number of filament bars used to create the digit. For example, the digit "8" uses all seven segments, "0" uses six, digits 2, 3, 5, 6 and 9 use five segments, etc. These whole-digit luminance variations were taken into account in the selection of 3-digit numbers to be presented to the observer trial-to-trial.

3. Size

Two display sizes were used in the experiments: large and small. The large display was defined by the dimensions of the 7-segment units, 8 mm in height and 4 mm in width. The small display was created optically by inserting a negative lens 11 cm in front of the display, a distance which halved the digit image to 4 mm in height and 2 mm in width. The lens and its effect on display size are illustrated in Figures 3 and 4.

The range of viewing distance was limited by the apparatus design between a near setting of 5 cm and a far setting of 64 cm. Using the digit height as the primary dimension of display size, visual angle of the large display ranged between 9°6' and 43 arc-minutes. Similarly the visual angle of the small display at the nearest possible viewing distance was 4°35', and at the far extent of the apparatus, 21 arc-minutes. Figure 5 shows the visual angle subtended at

Table 5. Whole-Digit Luminances for Display Filters
(1° spot covering digit; photopic)

Digit	Clear Display at 1000 ft-L	579 nm Filter at 34.0 ft-L	552 nm Filter at 32.0 ft-L	503 nm Filter at 7.6 ft-L
8	46.5	3.43	2.80	.74
0	40.5	2.98	2.45	.64
2,3,5,6,9	34.0	2.50	2.05	.54
4	28.0	2.07	1.72	.45
7	21.4	1.57	1.35	.34
1	14.5	1.09	.90	.24

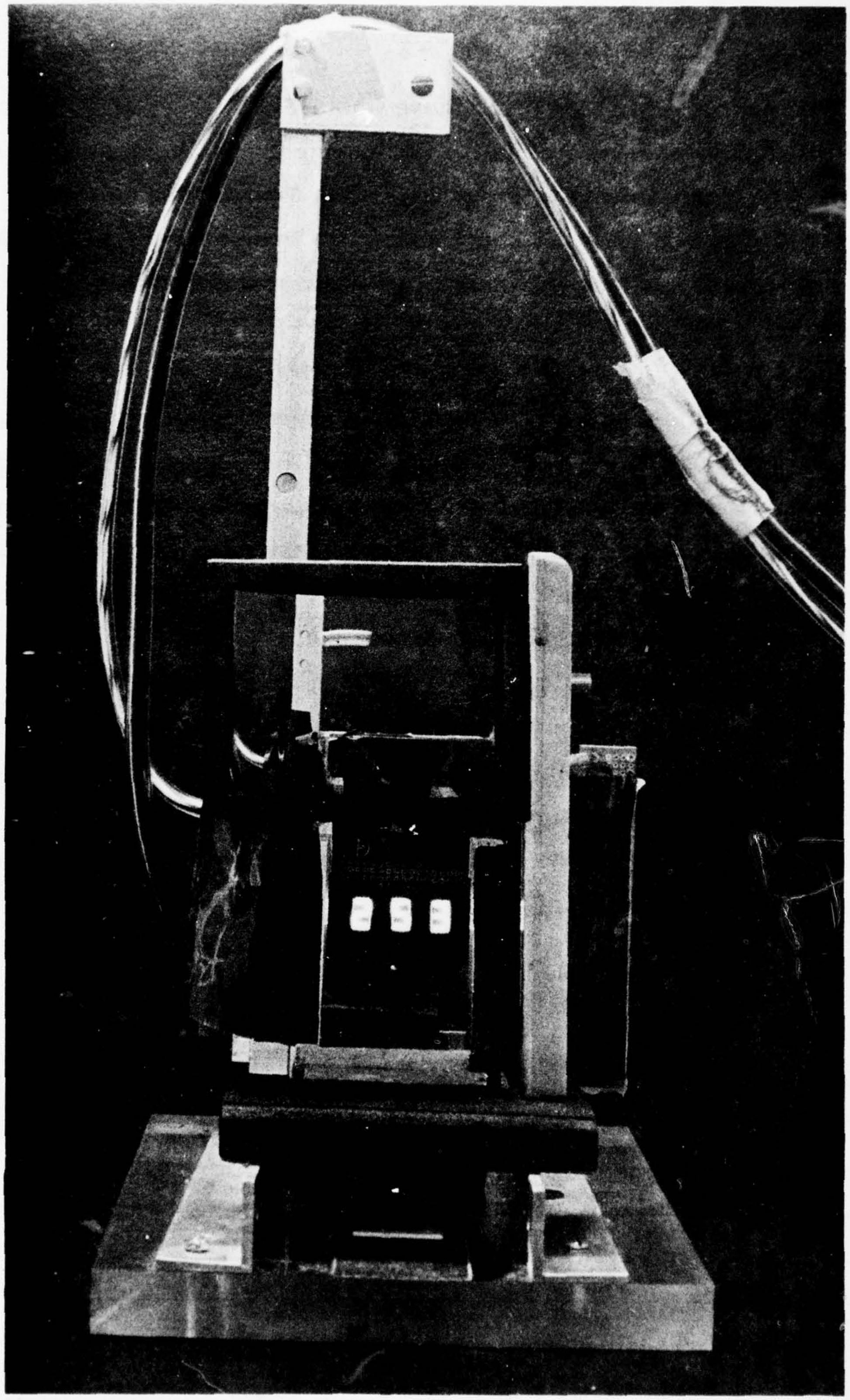


Figure 3. Large-Sized Display Illustration

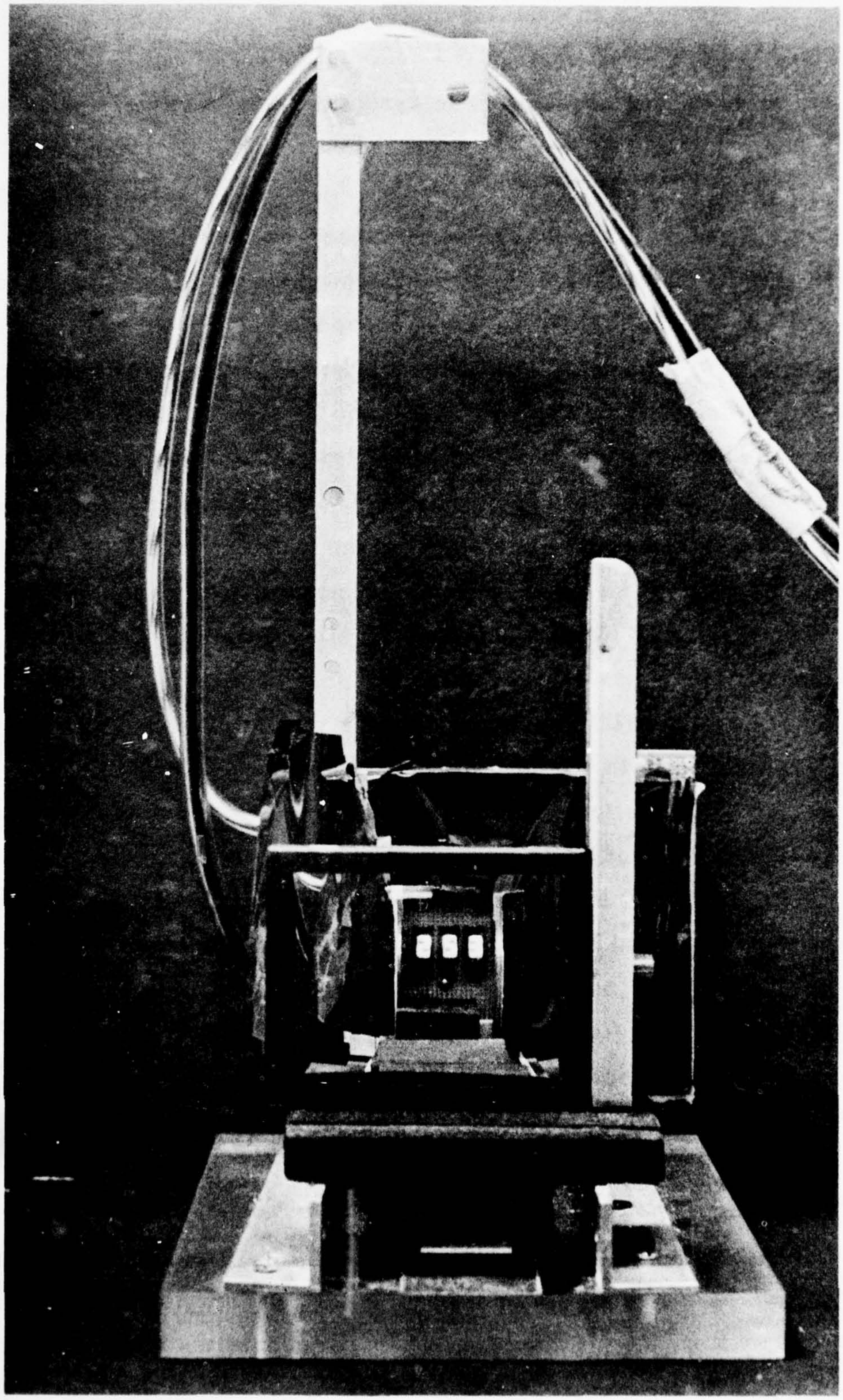


Figure 4. Small-Sized Display Illustration

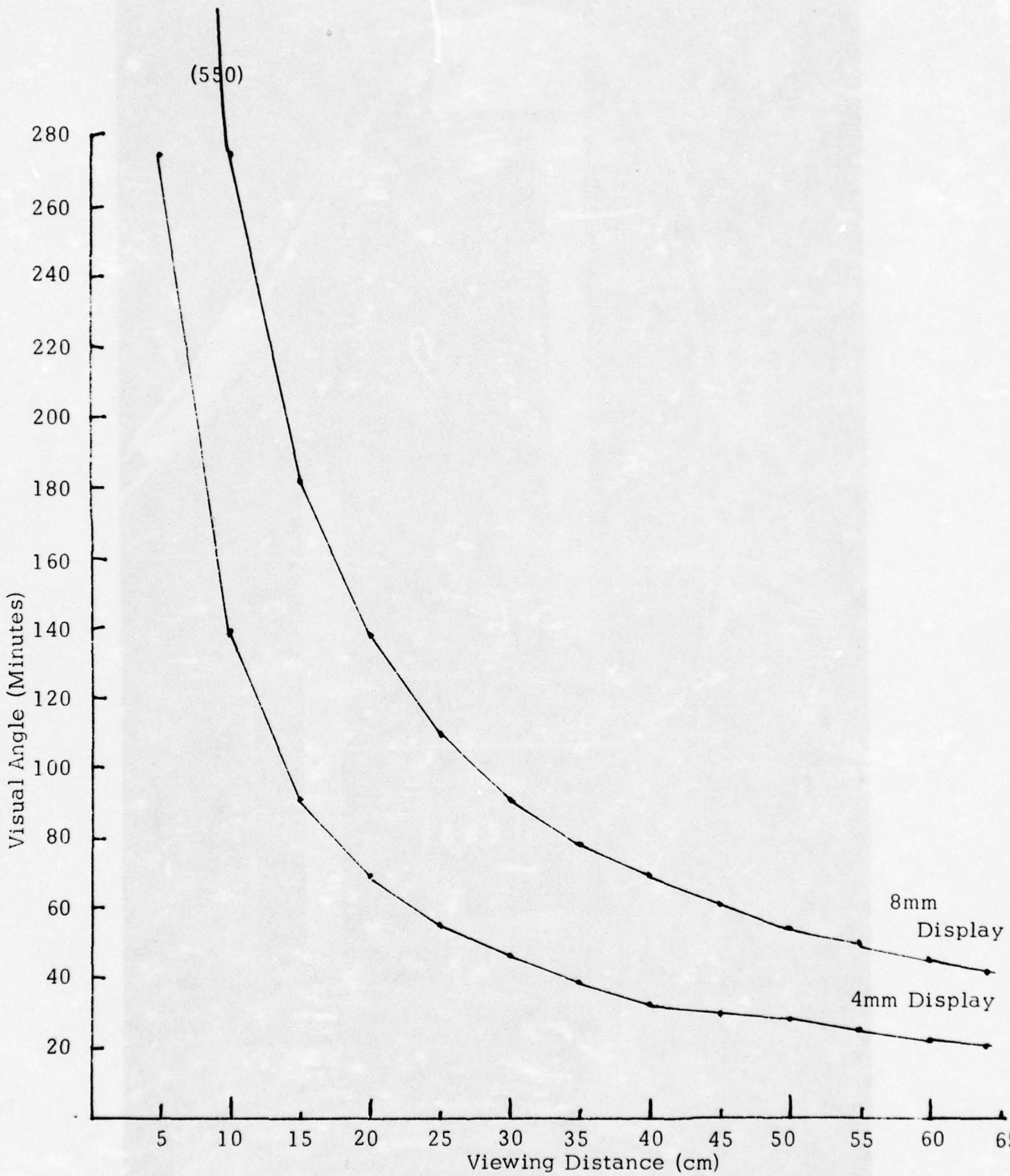


Figure 5. Visual Angle At the Eye of Large and Small Size Displays Through the Range of Viewing Distances

the eye by the large and small displays at viewing distances within the limits of the experiment.

C. Apparatus

A watertight test tank was constructed of 1/2-inch (1.27 cm) plexiglass. Overall dimensions of the tank were 36-inches (91.44 cm) in length, 31-inches (78.74 cm) in width and 22-inches (55.88 cm) in height. Liquid capacity of the tank exceeded 70 gallons (265 liters). A standard full facemask was mounted at one end of the tank. A drywell, open at the top was constructed to fit inside the tank; dimensions of the drywell were 8-inches (20.32 cm) by 31-inches (78.74 cm) by 16-inches (40.64 cm). With water in the test tank, the drywell was positively buoyant and pressed upward against aluminum railings which ran the length of the test tank on either side. Teflon rollers on the drywell engaged the underside of these aluminum rails enabling the drywell to roll along the longitudinal dimension of the test tank. The drywell also engaged a pair of threaded drive rods which were driven by a reversible motor at 1/4-inch (.635 cm) per second. Toggle switches mounted near the facemask at the viewing end of the test tank enabled the viewer to move the drywell longitudinally, in either direction, the full extent of the tank. With the drywell against the back wall of the test tank, 25-inches (64 cm) of water were between the faceplate and the face of the drywell; at the most forward position, 2-inches (5 cm) of water separated the two surfaces. A meter stick was mounted along the edge of the test tank and a pointer was mounted on the leading face of the drywell enabling the experimenter to note and record viewing distance; the linear distance between the faceplate and the face of the drywell containing the display.

The 3-digit display assembly fitted in the drywell in line with the facemask. A control box located at the experimenter's station permitted any combination of 3 digits between 000 and 999 to be displayed on any given trial. The display assembly included slots in front of the digits, machined to the dimensions of the interference filters and the neutral density filters. Forward

of the slots was the reduction lens mounted on a shaft so that it could be positioned in or out of the line of sight from the facemask to the 3-digit display. As the drywell was open along its top, the experimenter could modify the stimulus from trial-to-trial in any of three ways: display size was made large or small by changing the position of the reduction lens; display wavelength was varied by the selection of interference filters; display luminance, by the specific combination of neutral density filters placed in the slots in front of the display.

The test tank and drywell apparatus are shown in Figure 6.

D. Legibility Criterion

The several combinations of display variables (wavelength, luminance and size), viewed through four turbid water conditions, were evaluated by a measure of maximum legible viewing distance. A data collection procedure similar to the traditional psychophysical method of limits was used. The experimenter positioned the drywell beyond the limit of visibility for the turbidity condition, then turned over control of drywell position to the observer. The test observer moved the drywell forward until he could accurately read the 3-digit display. Using the identical combination of display variables the reverse procedure was followed, i.e., the display was positioned close to the observer who then moved the drywell further from the facemask to a limit of legibility. As a check on accuracy, the experimenter changed the 3-digit display readout four times using a pre-designed series of random numbers. The mean of the values of maximum viewing distance obtained from these two procedures was used as the dependent variable measure. The greater the value of maximum legible viewing distance, the more optimal was the combination of display variables for the turbidity condition.

E. Ambient Luminance

Both experiments were conducted in a small room provided by the Naval Special Warfare Group, Atlantic at the Naval Amphibious Base, Little Creek,

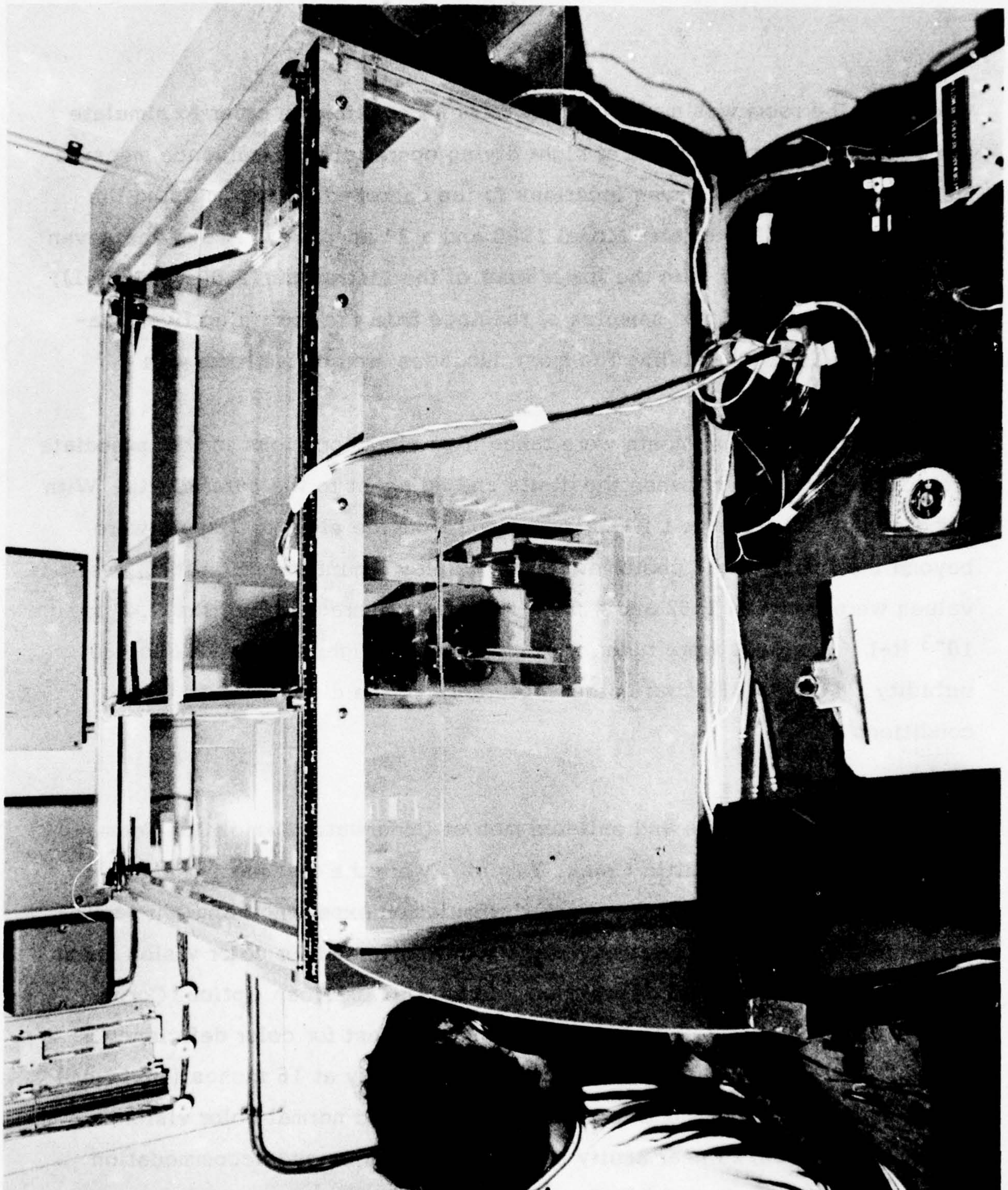


Figure 6. Test Tank and Drywell Apparatus

Virginia. The room was made as light proof as possible in order to simulate the dark surroundings typical of night diving operations. Luminance measurements were taken from seven locations in the darkened test room using the Spectra Pritchard Photometer Model 1980 and a 3° aperture. Two of the seven locations were darker than the lower limit of the instrument (1.00×10^{-5} ft-L); average luminance of two samples of readings from the remaining five locations was 2.10×10^{-5} ft-L. The most luminous area of the room was 4.30×10^{-5} ft-L.

Luminance measurements were taken from eight locations in the immediate area of the display: between the digits and adjacent to the outer digits. With the display luminance at 1 ft-L all readings from the eight test spots were beyond the limits of the photometer; at a display luminance of 30 ft-L, test values were between 2.62 and 4.10×10^{-3} ft-L; average value was 3.44×10^{-3} ft-L. Readings were taken with a 2' spot through 26 cm of Harbor-30 turbidity. Figure 7 illustrates the appearance of the display under these conditions.

F. Test Participants

Twenty-one officers and enlisted men of Underwater Demolition Team, Twenty-One (UDT-21) Little Creek, Virginia, were the test participants. Eleven men participated in the 'Harbor' simulation experiment and ten participated in the 'Ocean' simulation. Each man was tested for color vision, near visual acuity and accommodation near point. The American Optical Corporation's Pseudo-Isochromatic Plates were used to test for color deficiency. The RAF Near-Point Rule was used to test near acuity at 16 inches (40.64 cm) and to determine accommodation near point. All had normal color vision; twenty men had 20/20 near acuity and one 20/30; ages and accommodation near points are shown in Table 6. The twenty-one test participants are named and listed alphabetically in Appendix C.

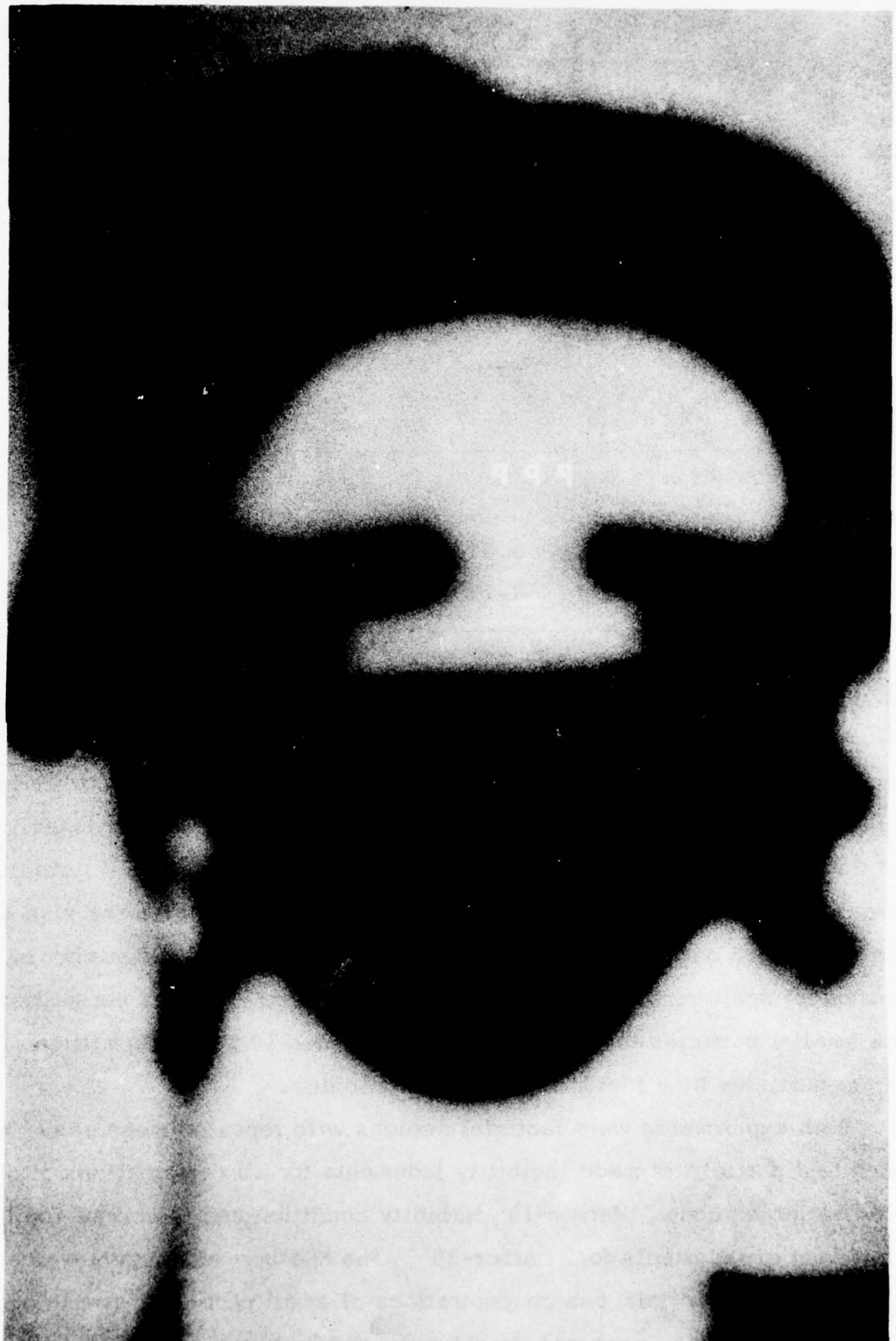


Figure 7. Display As Seen Through 'Harbor'-30 Turbidity Condition

Table 6. Test Participant Characteristics

	Experiment #1	Experiment #2
Number of Test Participants	11	10
Age		
Mean	27	30
Range	22-37	23-39
Accommodation Near-Point		
Mean	5.5" (14 cm)	5.5" (14 cm)
Range	4-7" (10-18 cm)	4-8" (10-20 cm)

G. Experimental Design and Procedure

Two separate experiments were conducted: Experiment #1 examined legibility of display variations under two concentrations of 'Harbor' turbidity, 10 and 30 parts per million equivalent suspended sediment load; Experiment #2 was a similar experiment using two concentrations of 'Ocean' turbidity. The differences between the two artifically turbid waters were the size of the suspended particles,1 vs 25 micrometer diameter, and the number of individual scatterers per condition of concentration: 10 parts per million of the smaller particles included more particles than 10 parts per million of the larger particles by a factor of several magnitudes.

Both experiments were factorial designs with repeated measures; i.e., each test participant made legibility judgments for all combinations of display variables under 'Harbor-10' turbidity condition and then repeated the entire set of judgments for 'Harbor-30'. The 'Harbor' experiment was a 2 x 2 x 3 x 4 factorial: two concentrations of small particles, two display sizes, three wavelengths and four levels of luminance. The 'Ocean'

experiment was a 2 x 2 x 3 x 3 factorial design: two particle concentrations, two display sizes, three display wavelengths and three display luminances. Table 7 presents the specific values of the variables included in the two experiments. Additional trials were included in the 'Harbor' experiment to extend the luminance variable beyond the level (10 ft-L) at which all wavelengths could be compared in the factorial design. The 552 nm (green) and 579 nm (yellow) wavelengths extended to 30 ft-L and the unfiltered display was extended to 1000 ft-L.

Test participants were briefed as to the purpose of the experiments, shown the apparatus, the display and the optical devices used to modify the display, practiced in the control of the drywell, and instructed about the trial-to-trial procedure. Next, the series of vision tests was administered in order to screen out any potential participants with less than adequate color

Table 7. Values of Experimental Variations

	'Harbor' Simulation (1 Micrometer Particles)	'Ocean' Simulation (25 Micrometer Particles)
Turbidity Concentration (ppm)	10 and 30	10 and 30
Display Wavelength (nm)	503 552 579	503 552 579
Display Size (mm)	8 x 4 4 x 2	8 x 4 4 x 2
Display Luminance (ft-L)	.1 .3 1.0 10	.003 .01 .03

vision or near acuity, and the accommodation near-point was determined. The test participant dark adapted for 30 minutes prior to the administration of the experimental trials.

Schedules of trials were prescribed which randomized size/luminance combinations within wavelengths. Half the test participants were tested in a yellow-green-blue order and half in the reverse. Three-digit display readouts were presented trial-to-trial according to a table of random numbers, and four 3-digit numbers were used on each trial. Certain constraints on complete randomness were imposed on the use of 0's, 8's, 1's and 7's in order to reduce variation in the total number of filaments illuminated per presentation. For example, given the 7-segment numeric displays, the presentation "111" would have used only 6 segments; "888" would have used 21.

The experimenter turned off the display, inserted the appropriate combination of filters to control luminance and positioned the reduction lens to control size according to the values required by the schedule of trials. The experimenter moved the drywell beyond the range of legibility for the turbidity condition, turned on the display, and turned over control of the drywell to the observer. The observer then put his face into the facemask and operated the control switches which moved the drywell. When the display was moved to a position where it could be accurately read by the observer, the experimenter recorded the faceplate-to-display face distance from the meter stick along the top of the test tank. Each observer made two settings per condition of wavelength/luminance/size in each of two concentrations of artificially turbid water. The arithmetic mean of the two settings was used to define maximum legible veiwing distance for each observer for each combination of display/turbidity variations. These values were used in the repeated measures variance analyses and are the cell entries in the raw data tables of Appendix D.

III. RESULTS

A. Evaluation of the Turbidity Simulations

Underwater visibility experimentation in the past has included descriptions of turbidity in terms of its optical effects and not in terms of its physical characteristics. One of the main purposes of the present experimental program was to simulate the physical characteristics of naturally turbid waters so that the viewing medium could be accurately recreated in future experiments and so that optical and perceptual effects could be attributed to known physical properties of the experimental water. Two areas of evaluation were addressed: validity of the simulation vis-a-vis samples of natural water, and stability of the turbidity condition over time. The first area, validity, concerns prediction; results of perceptual experiments in artificially turbid waters can potentially predict perceptual outcomes in natural water to the extent that the artificial water is an accurate representation of the natural. The second area, reliability, is basic to the first since the accuracy of prediction from artificial to natural water is limited in the first place to the stability of the characteristics of the experimental water over the period of the data collection.

1. Reliability of the Artificially Turbid Waters

Four samples of artificially turbid waters were prepared and used as viewing media for experiments in display legibility under water. These samples were labelled 'Harbor-10', 'Harbor-30', 'Ocean-10' and 'Ocean-30'. 'Harbor' and 'Ocean' designations specified 1 vs 25 micrometer particle diameters used to represent median sizes of naturally-occurring particles; 10 and 30 designated the concentrations of particles in parts per million: milligrams of suspended material per kilogram of water. The reliability issue concerned the extent to which a given turbidity condition remained constant over the interval of time during which the legibility experiment was conducted. Although air bubblers were used between test trials to stir the water and

maintain the particles in suspension, it was expected that some settling would occur, particularly with the larger particle turbidity conditions.

Stability of the turbidity condition over time was assessed by measuring the optical transmissivity of samples of water taken from the test tank at intervals during each experiment. Measurements were made using a Beckman Model DK Spectrophotometer which compared optical transparency of the turbid water sample to a sample of distilled water over a range of wavelengths. The transparency readings were converted to optical density according to the formula:

$$D = \log\left(\frac{100}{\%T}\right)$$

where:

D = optical density

%T = percent of incident light transmitted through a 10 cm path length of turbid water as compared to a 10 cm path of distilled water.

Since the legibility experiments included wavelengths in the range 503-590 nm, the portion of the spectrum between 500 and 600 nm was examined via spectrophotometry for all samples of the four turbidity conditions. Figures 8, 9, 10 and 11 show the optical density value plotted against wavelength in 10 nm intervals between 500 and 600 nanometers. Harbor-10 water was sampled only twice which provided an estimate of the amount of settling which occurred over a five week interval. However, the first sample was taken on 15 April and the first observer was not tested until 20 April, so the variation in turbidity during the testing interval is not known. Other turbidity conditions were sampled more frequently and coincident with the test schedule as shown in Table 8. Average standard deviations of the optical density of these samples were .1245, .0066 and .0176, respectively; values approximately 8%, 5%

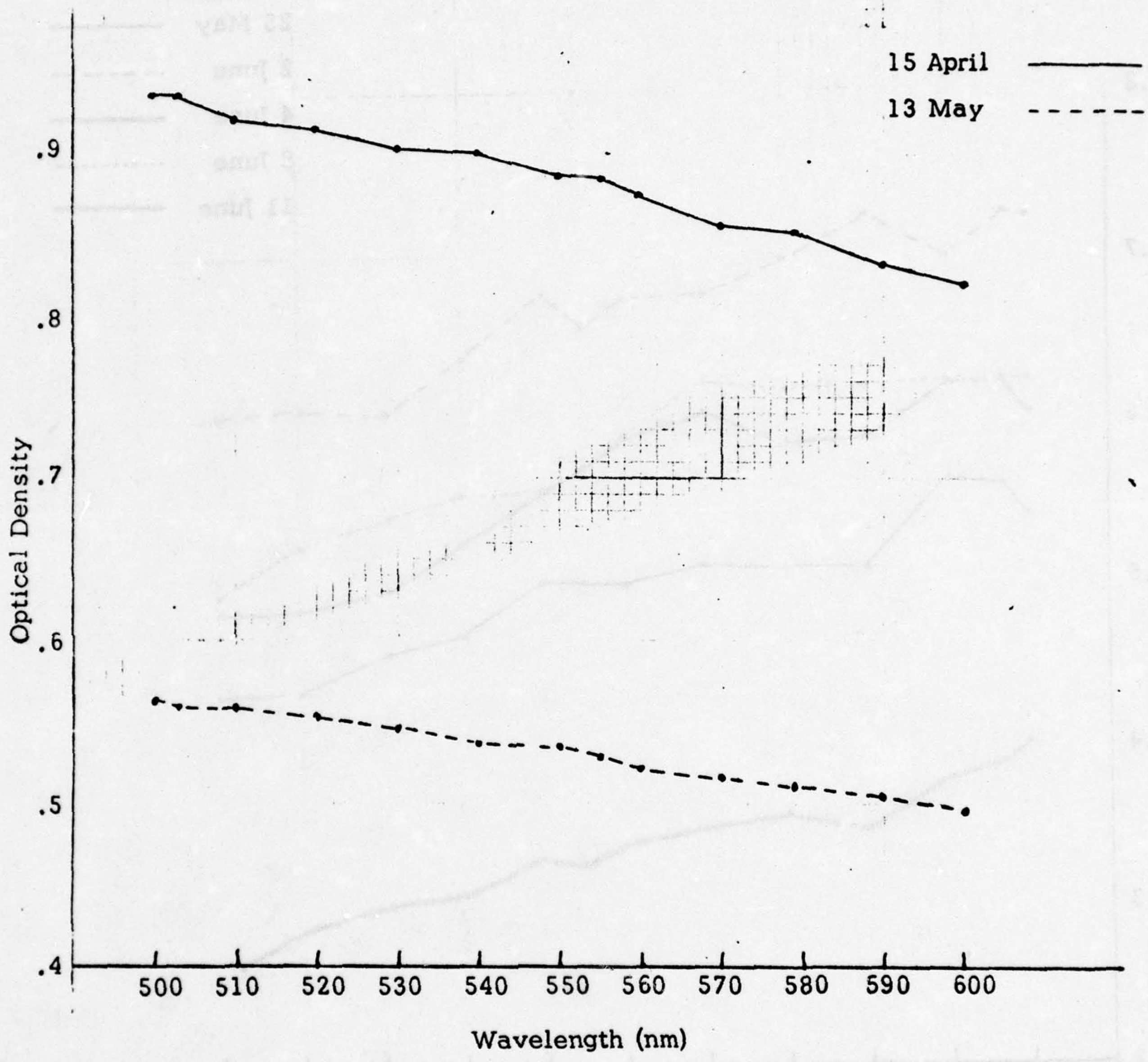


Figure 8. Optical Density vs Wavelength for Two Samples of Harbor-10 Turbidity

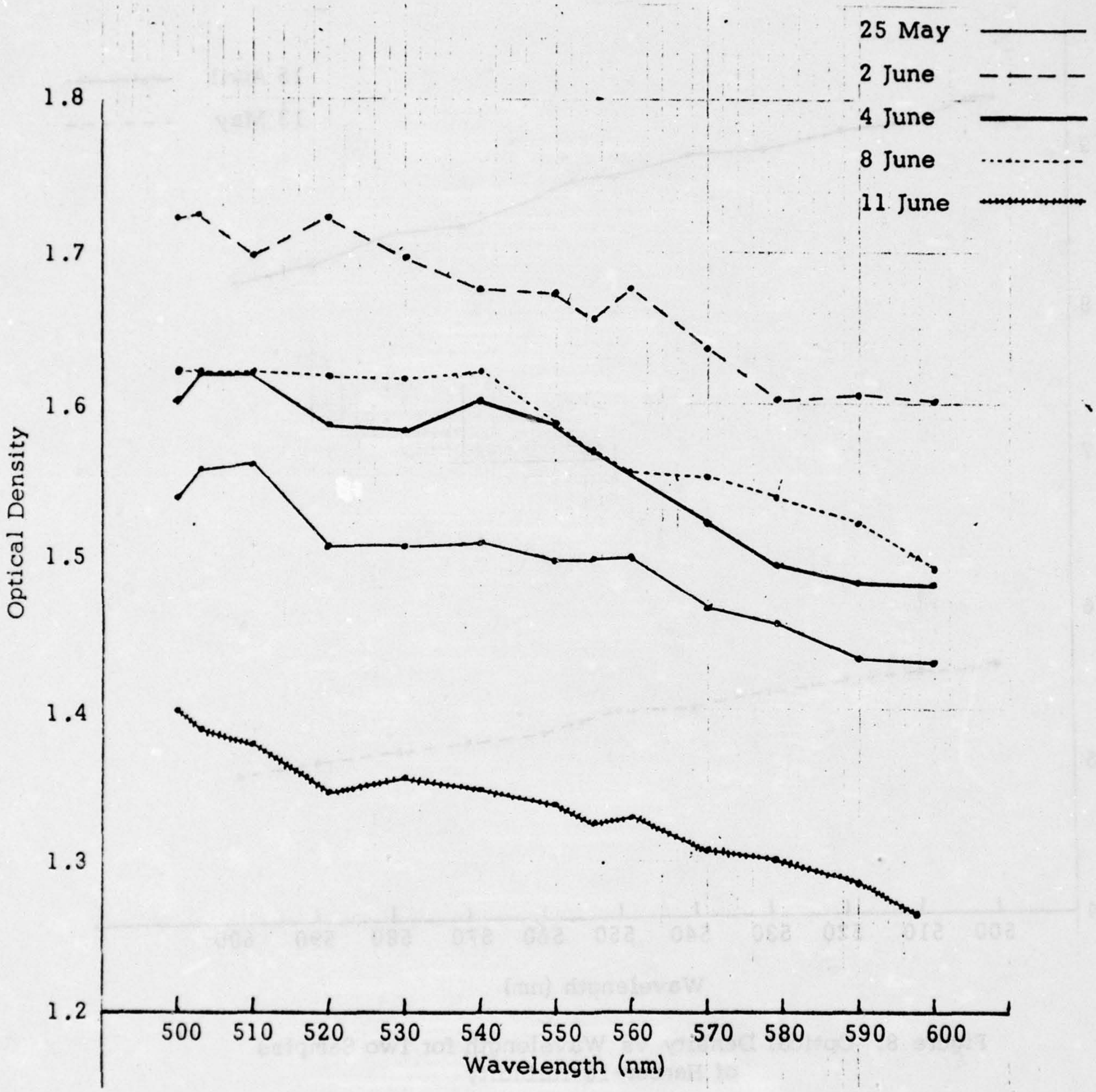


Figure 9. Optical Density vs Wavelength for Five Samples of Harbor-30 Turbidity

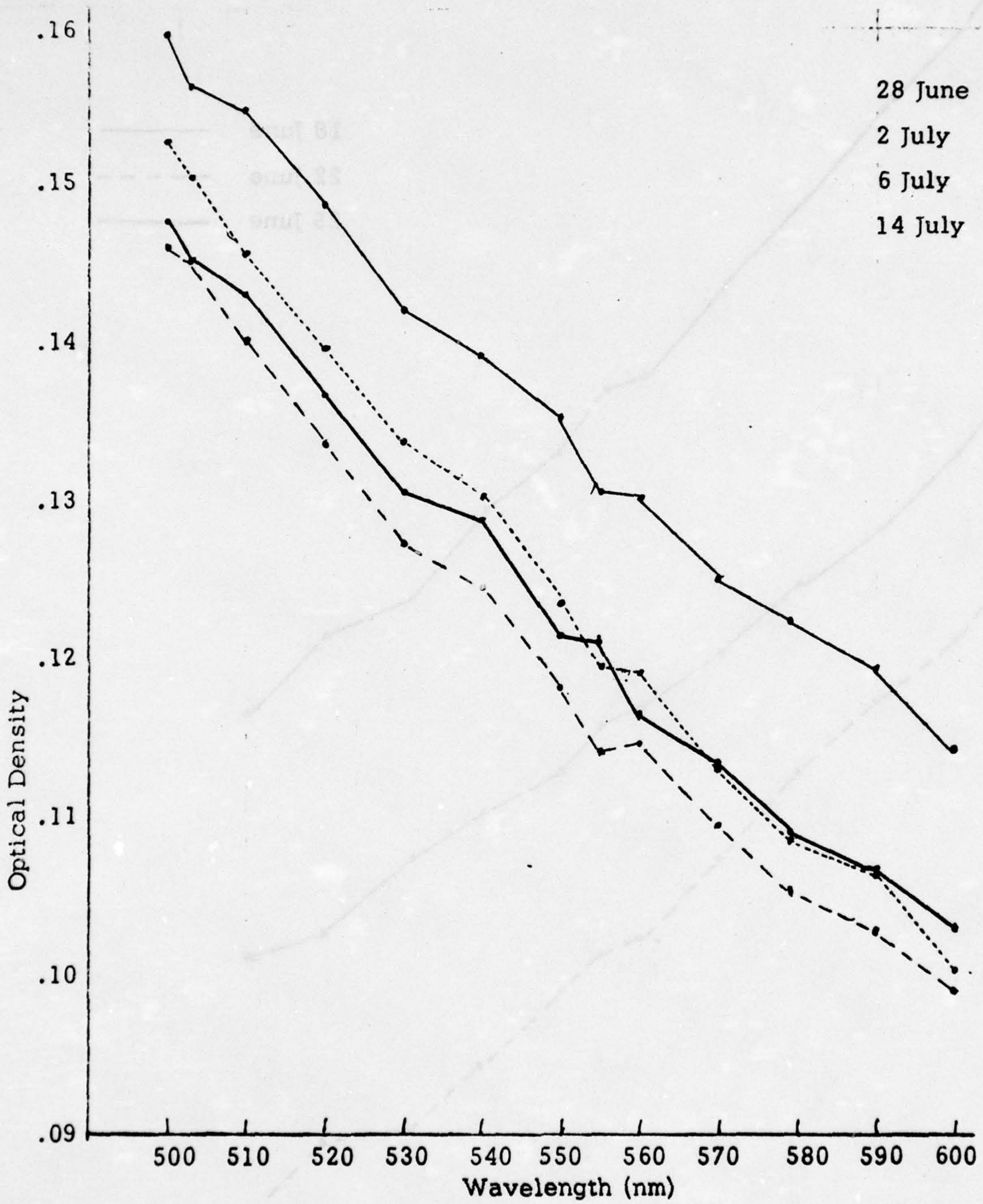


Figure 10. Optical Density vs Wavelength for Four Samples of Ocean-10 Turbidity

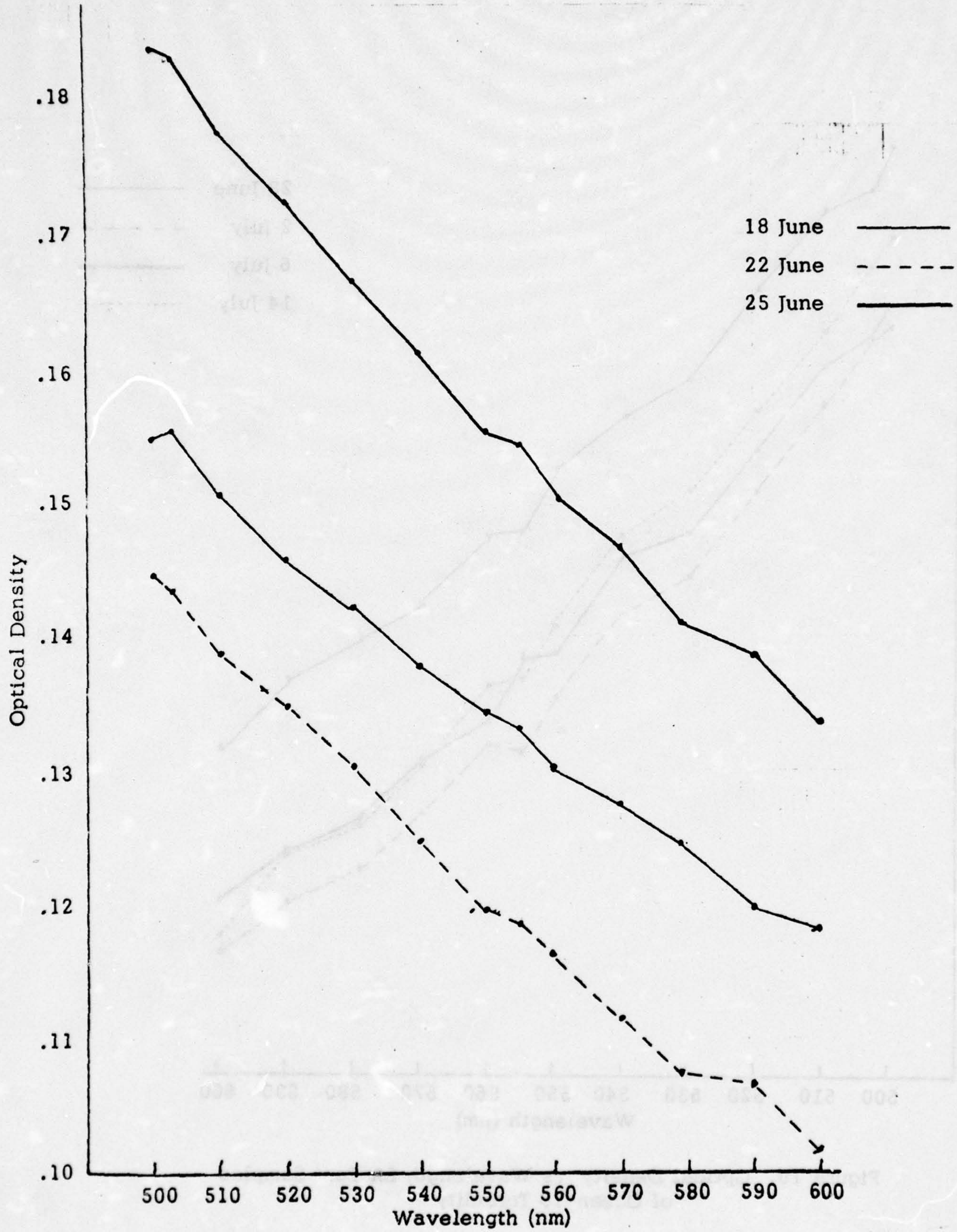


Figure 11. Optical Density vs Wavelength for Three Samples of Ocean-30 Turbidity

12% of the means of the three distributions. The maximum differences among the several samples of a given turbidity condition were approximately .3 log unit optical density for Harbor-30, .015 log unit for Ocean-10, and .035 log unit for Ocean-30. Temporal patterns of the sample-to-sample differences were not regular and did not suggest a successive settling of the particles over time. Differences were more likely a result of variations in the effectiveness of the stirring technique employed; i.e., air bubblers placed in the bottom of the test tank between trials.

Table 8. Schedule of Trials and Turbidity Samples

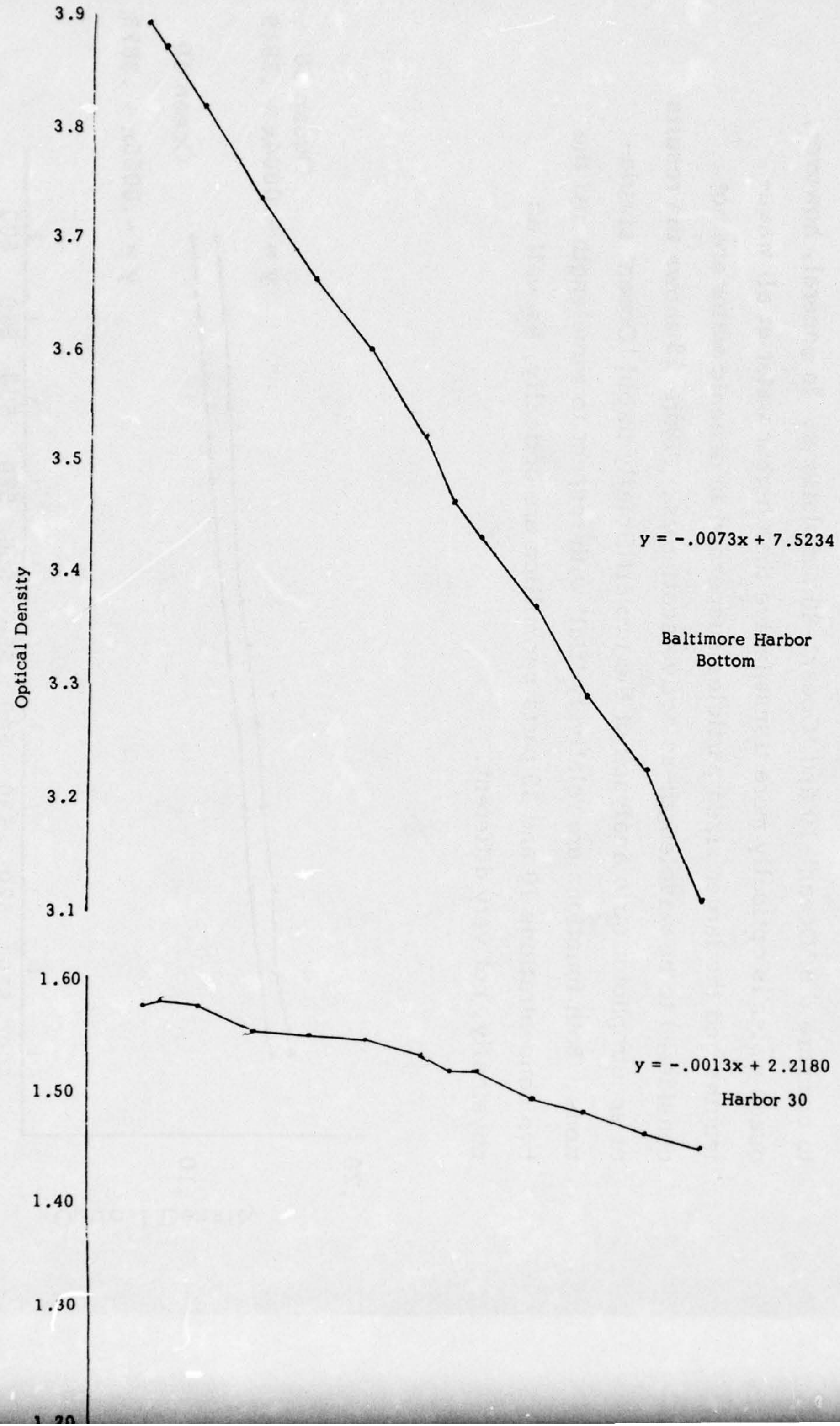
Turbidity Condition	Data Collection	Water Sampling
Harbor-10	20 April - 12 May	15 April 13 May
Harbor-30	26 May - 10 June	25 May 2 June 4 June 8 June 11 June
Ocean-30	16 June - 24 June	18 June 22 June 25 June
Ocean-10	29 June - 14 July	28 June 2 July 6 July 14 July

2. Validity of the Artificially Turbid Waters

Harbor-10 and Harbor-30 simulations were compared in optical properties to samples of water taken from the Upper Chesapeake Bay. Natural water samples were taken at the surface, 5 meters depth, and near the bottom at several locations between the Bay Bridge and Baltimore Harbor. The samples were collected on July 8, 1976 from the U.S. Naval Academy oceanographic research vessel. The first samples were taken at the Bay Bridge at 10:30 a.m. after which the vessel proceeded toward Baltimore Harbor, collecting samples along the way. The last samples were taken in Baltimore Harbor at 12:30 p.m. after which the vessel returned to the Naval Academy dock at 2:30 p.m. The samples were immediately analyzed in the spectrophotometer in the order in which they were taken so that the maximum time between collection and analysis was about 4 hours.

The samples were collected by means of a pump and hose arrangement. One end of a hose was weighted and lowered to the depth of interest, while the other end was attached to a pump placed on the deck of the research vessel. Samples could be taken very quickly since a hose 50 feet long and .75 inches in diameter has a total volume of only 0.15 cubic feet, allowing total flushing of the hose eight times per minute at a pumping rate of 10 gallons per minute.

Mean optical density values of the Chesapeake Bay samples were plotted and compared to mean values of the several samples taken of Harbor-10 and Harbor-30. The several plots of optical density vs wavelength are shown in Figure 12. Additionally each turbidity condition was described by the regression equation for optical density (y) as a function of wavelength (x). Harbor-10 optical properties are approximately midway between those of the Chesapeake Bay at 5 meters and near the bottom at 13 meters; Harbor-30, while more opaque than the near-bottom Bay water does not approximate conditions near the bottom of Baltimore Harbor. The slope of the wavelength


Optical Density
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
1.60
1.50
1.40
1.30
y = -.0073x + 7.5234
Baltimore Harbor
Bottom
y = -.0013x + 2.2180
Harbor 30

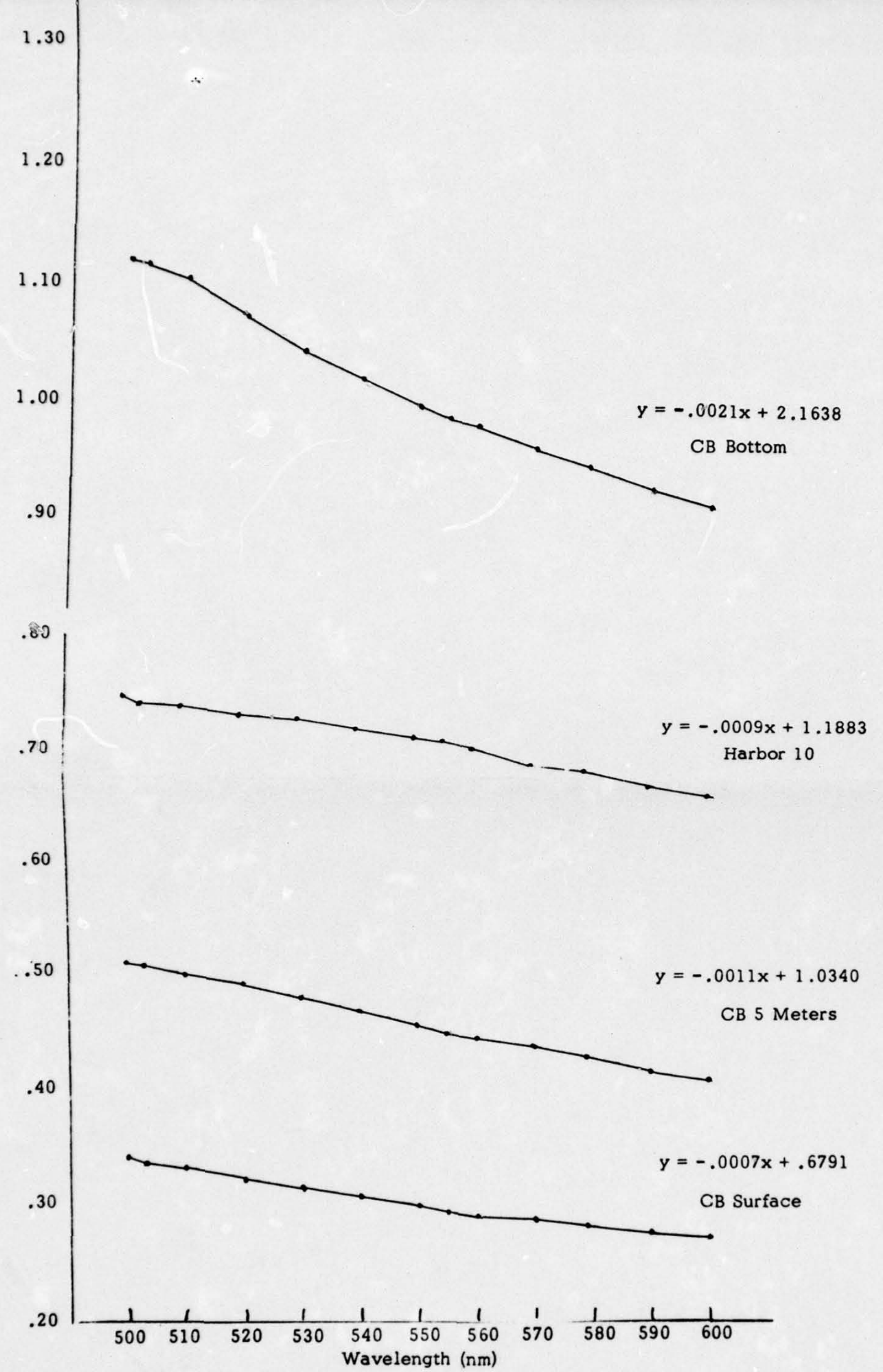


Figure 12. Optical Density vs Wavelength for Natural and Simulated Waters

vs optical density functions for both Harbor-10 and Harbor-30 were somewhat less steep than the naturally turbid water samples which they most closely approximated in opaqueness. Natural Bay and Harbor waters favored transmission of longer wavelengths relative to the shorter wavelengths and this characteristic, while in the same direction, was less pronounced in the artificially turbid simulations.

No data were available from near shore ocean environments with which to compare the 'Ocean'-10 and 'Ocean'-30 simulations. In general, however, ocean water is optically more transmissive than harbor water at all wavelengths and the larger sized particles suspended in oceanic water are not considered to be wavelength-selective scatterers. Figure 13 shows the results of spectrophotometric analyses of the two artificially turbid 'Ocean' simulations. Both functions are relatively 'flat' with respect to wavelength and the two concentrations 10 and 30 parts per million are optically, as well as physically, not very different.

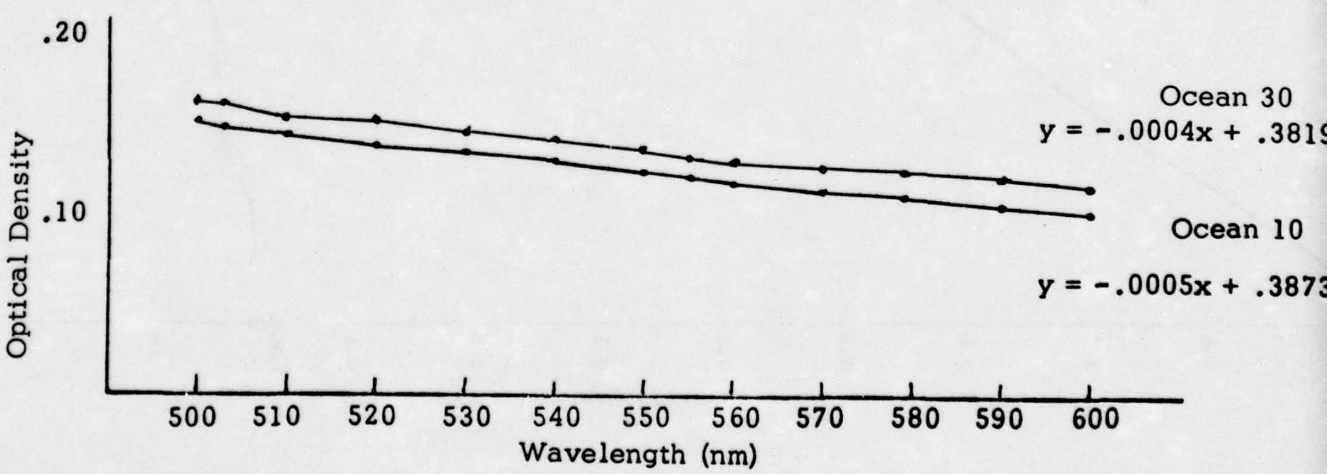


Figure 13. Optical Density of Artificially Turbid 'Ocean' Water

B. Display Legibility in 'Harbor' Turbidity

The limits of legible viewing distance permitted by the test tank were between 5 and 64 centimeters (approximately 2 and 25 inches). In the turbidity conditions defined by a low concentration of small-sized particles, Harbor-10, the range of display luminances between .01 and 1000 ft-L exhausted these limits. At display luminances of .003 ft-L and less, the drywell containing the display could not be moved close enough for legible viewing; at luminances beyond 1000 ft-L, the display was easily legible to all subjects at the most distant position permitted by the apparatus. While response data were collected at half-log intervals of luminance between .01 and 1000 ft-L, a more restricted set of values was used for the analysis of variance. Luminance values less than .1 ft-L could not be seen legibly through the higher density turbidity, Harbor-30. Since the use of narrow bandwidth interference filters severely reduced luminance of the display, values above 10 ft-L eliminated the 503 nm wavelength and values beyond 30 ft-L eliminated the 552 and 579 nm wavelengths. Consequently, although the graphic presentations of results will show means of data collected at all luminances included in the experiment, the analysis of variance included only four levels of luminance .1, .3, 1.0 and 10 ft-L.

Table 9 is the analysis of variance summary table for the viewing distance data obtained via a repeated measures design in two concentrations of small-particle turbidity, Harbor-10 and Harbor-30. As indicated in the table, each of the main effects, particle concentration, display wavelength, size, and luminance was statistically significant. Three second-order interactions and one third-order interaction were also significant. In addition to the significance tests, an estimate of proportion of variance accounted for by the significant treatment effects was calculated, ω^2 (Hays, 1973). Variations in particle concentration, display luminance and the concentration x luminance interaction accounted for 89% of the total variance in legible viewing distance responses. The results are illustrated in Figures 14, 15, 16

Table 9. Analysis of Variance Summary Table for Display Legibility in 'Harbor' Turbidity

Source	df	MS	F	ω^2
Particle Concentration (C)	1	32188.5208	491.19**	.60
Display Wavelength (W)	2	149.3495	5.75*	
Display Size (D)	1	1011.3912	73.64**	.02
Display Luminance (L)	3	4333.0516	1116.33**	.24
CW	2	11.4649	1.04	
CD	1	253.6137	42.88**	
CL	3	914.7305	481.29**	.05
WD	2	5.0856	2.78	
WL	6	120.8155	69.99**	.01
DL	3	3.9468	2.72	
CWD	2	1.6270	1.17	
CWL	6	32.6286	23.83**	
CDL	3	.3539	<1	
WDL	6	.7985	<1	
CWDL	6	1.2105	<1	

*p < .05

**p < .01

and 17. Figure 14 reveals the strong effects of display luminance and particle concentration indicated by the analysis of variance significance tests and Hay's strength of association statistic. Maximum viewing distance increased linearly with logarithmic increases in display luminance, and the slope of the relationship was markedly influenced by particle concentration.

Figure 15 shows the marginal although statistically significant effect of variations in display size when viewed through turbid Harbor water. The large-sized display (8 x 4 mm), was consistently read at greater viewing distances than the smaller display (4 x 2 mm) at equivalent luminance. The significant particle concentration x display size interaction is also apparent from Figure 15; in the more turbid condition, Harbor-30, the effect of display size on viewing distance was lessened as compared to the Harbor-10 condition.

Figures 16 and 17 illustrate the significant Wavelength by Luminance interaction and the significant Concentration by Wavelength by Luminance interaction. Figure 16 shows the WL interaction; as luminance levels decreased below 1.0 ft-L the blue/green display (503 nm wavelength) was legibly viewed at greater distances than the other wavelengths. Figure 17 shows that as particle concentration increased, the effect of wavelength was diminished; an effect similar to that of concentration on display size.

C. Display Legibility in 'Ocean' Turbidity

Ten dark-adapted observers made maximum legible viewing distance settings for displays which varied in luminance, size and wavelength and which were viewed through two concentrations of 'Ocean' turbidity. Because of the difference in size between the Ocean and Harbor particles, far fewer particles (and, therefore, individual scatterers) defined Ocean-10 as defined Harbor-10 by several magnitudes. Furthermore, the differences between 10 and 30 parts

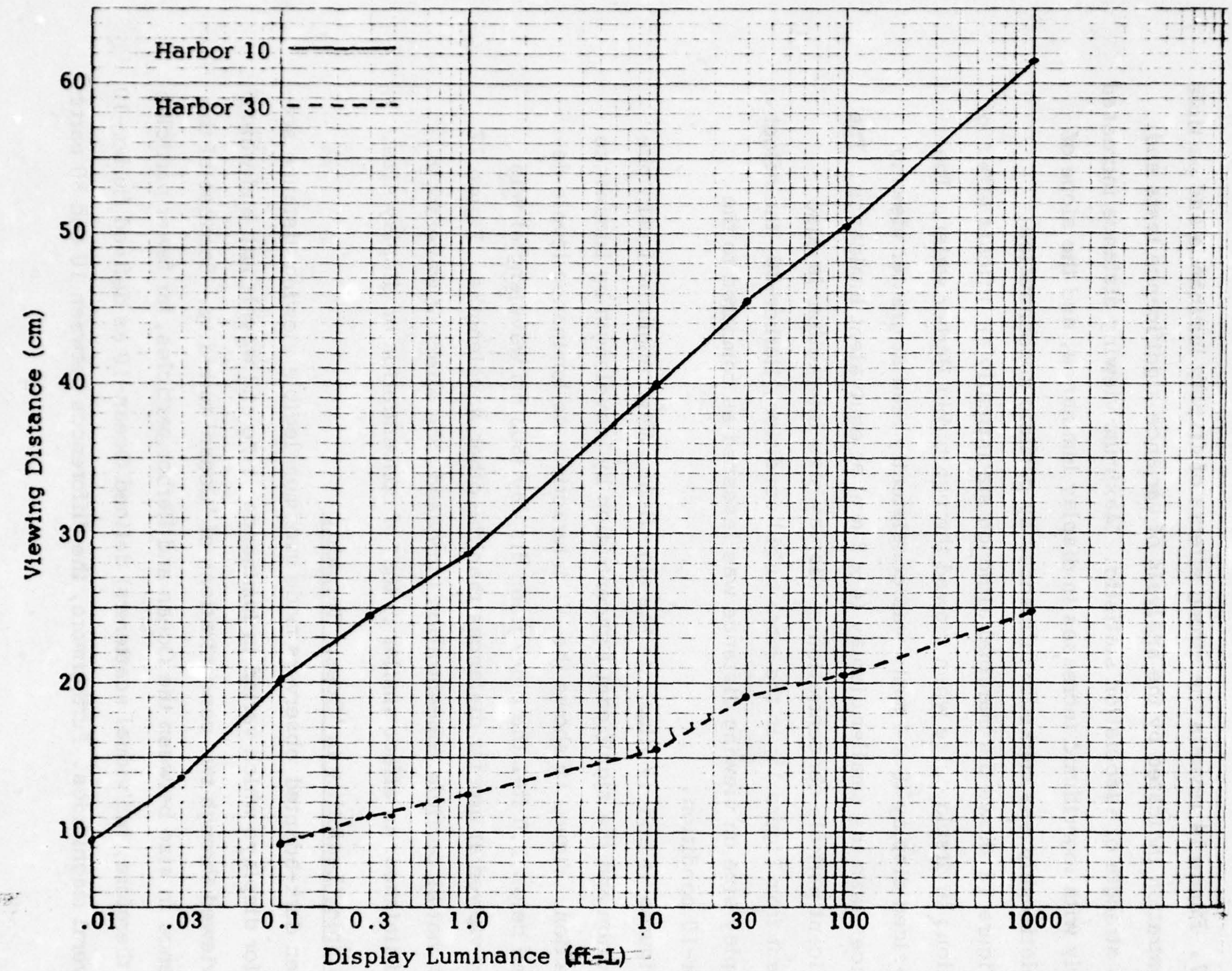


Figure 14. Maximum Legible Viewing Distance in Harbor Turbidity as a Function of Display Luminance

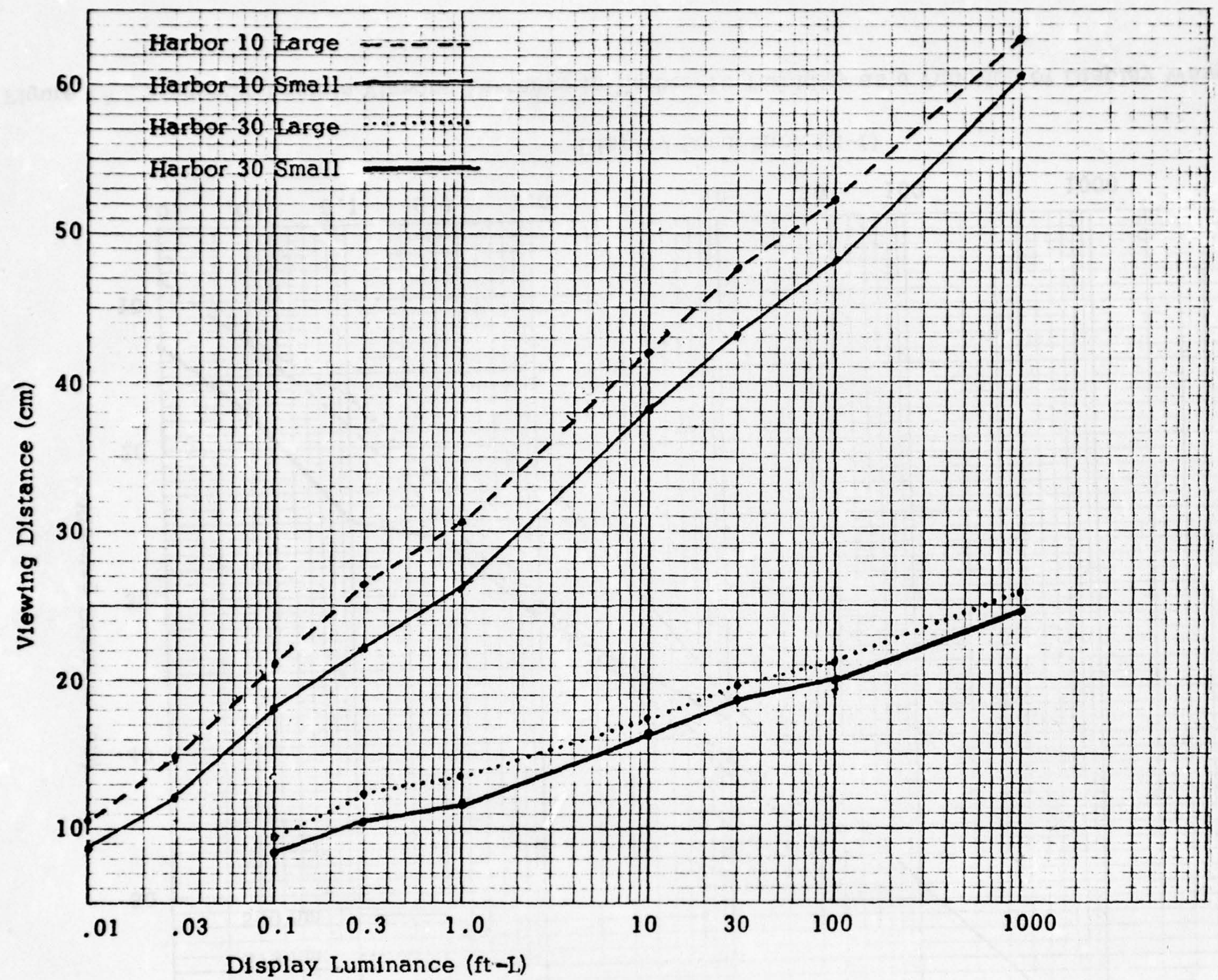


Figure 15. Maximum Legible Viewing Distance in Harbor Turbidity as a Function of Display Size

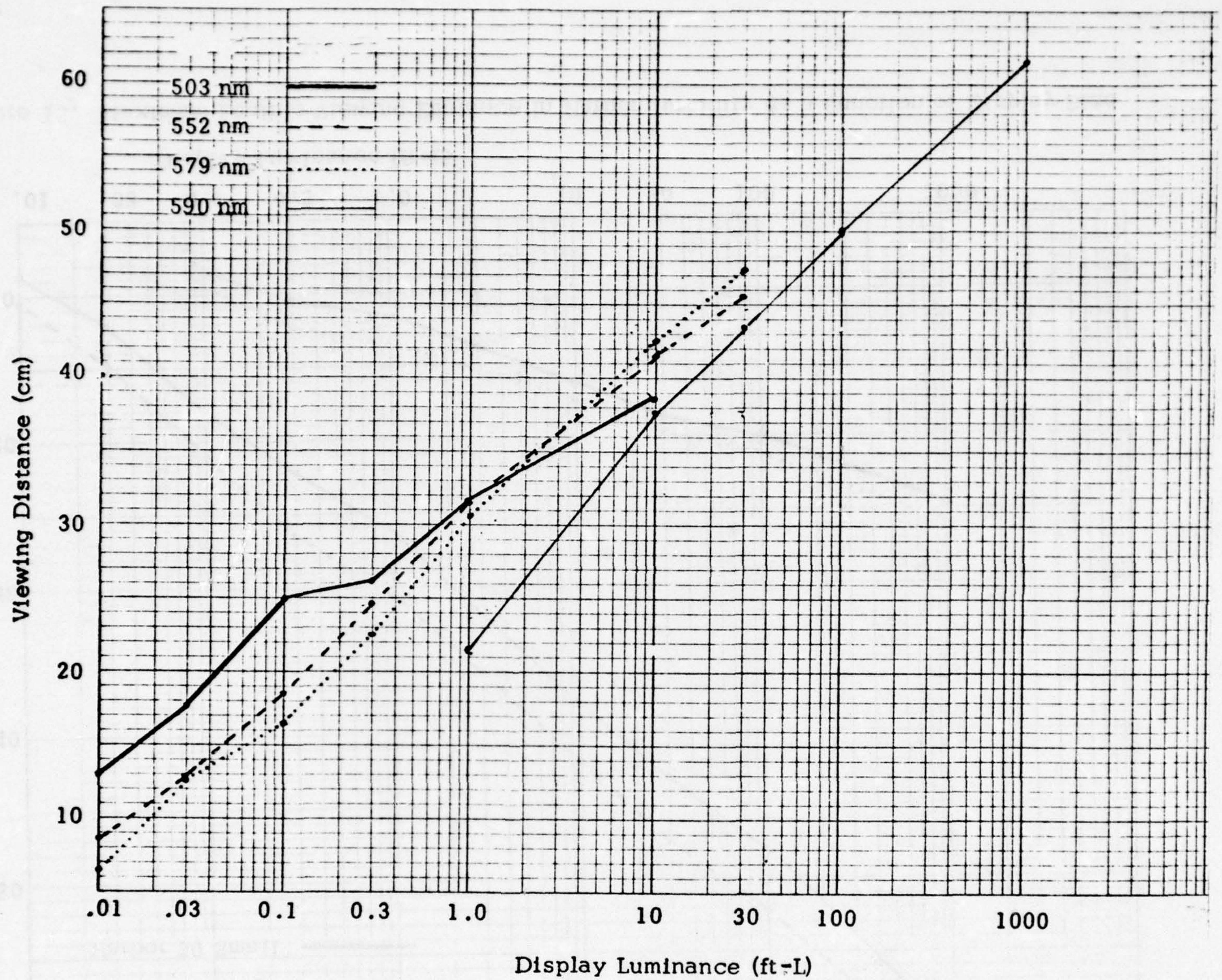


Figure 16. Maximum Legible Viewing Distance in Harbor-10 Turbidity as a Function of Display Wavelength

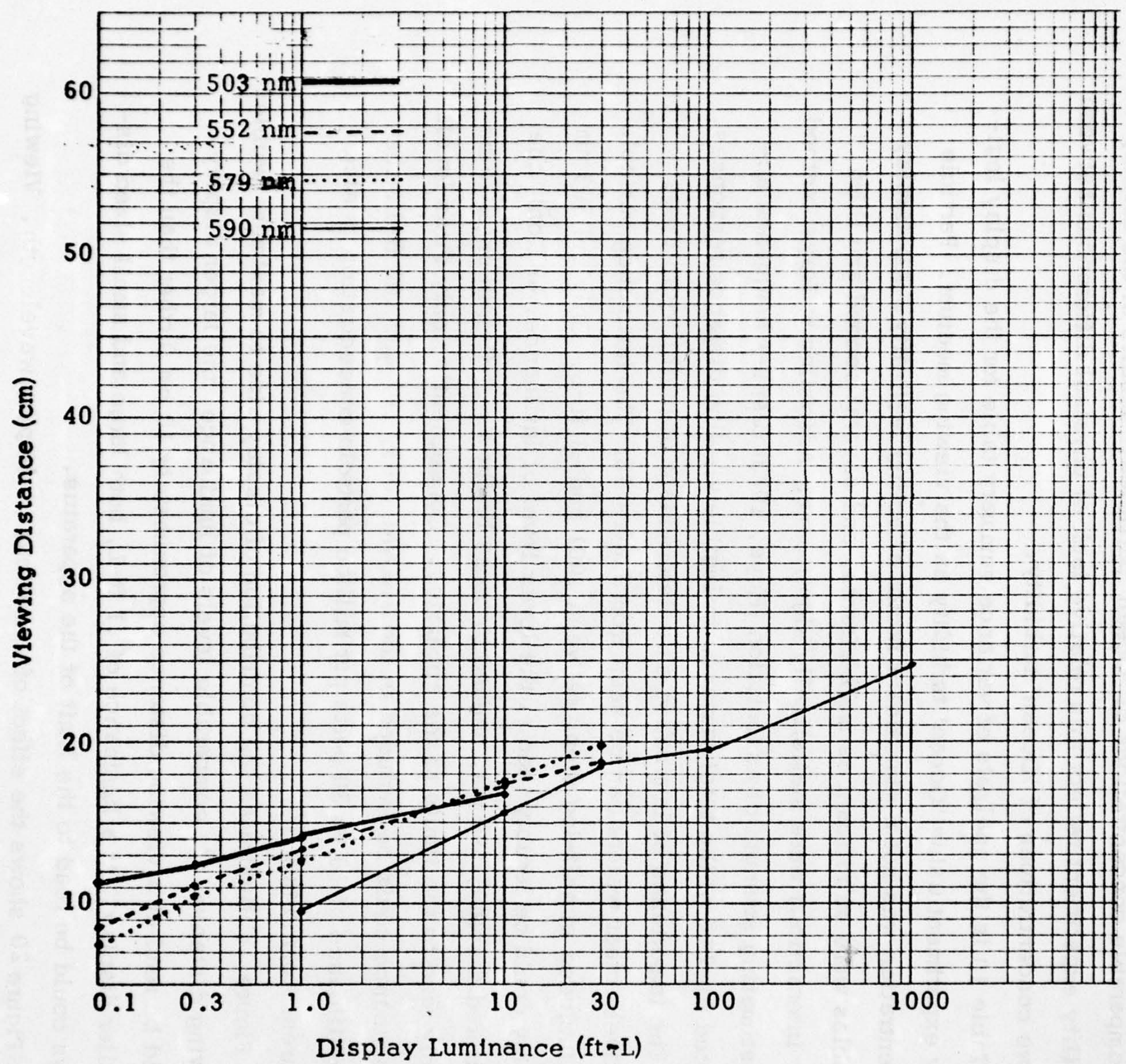


Figure 17. Maximum Legible Viewing Distance in Harbor-30 Turbidity as a Function of Display Wavelength

per million of the small 'Harbor' particles was a far larger difference than the comparable concentrations of 'Ocean' particles. Results of the display legibility experiment reflect this relative lack of physical differences between the two concentrations of 'Ocean' turbidity.

Table 10 is the analysis of variance summary table for the display legibility experiment using 'Ocean' turbidity as the viewing medium. Particle concentration was not a significant factor affecting legibility. All display variables were significant as main effects, and several second and third order interactions were statistically significant. According to Hays' method for estimating strength of association (Hays, 1973) display luminance accounted for 73% of the total variance in legible viewing distance responses.

The importance of luminance as a determinant of legibility in these relatively clear waters can be seen from Figure 18. The luminance variable was included in half-log steps between .001 and .1 ft-L. Only the 503 nm display could be legibly read at the lower level of luminance, and only the unfiltered display, 590 nm, needed to be as bright as .1 ft-L in order to be legibly read to the limits of the apparatus. Consequently, only three levels of luminance could be included in the ANOVA: .003, .01 and .03 ft-L. The insignificance of 10 vs 30 parts per million particle concentration is also apparent from Figure 18.

Figure 19 illustrates the contribution of display size to maximum legible viewing distance. At comparable levels of luminance, the larger display could be read at a viewing distance approximately 10 cm further than the smaller display. At a luminance of .1 ft-L, both large and small sized displays could be read to the limit of the apparatus.

Figure 20 shows the effect of variations in display wavelength. Viewing distance was systematically related to wavelength, the shorter wavelengths being more legible than the longer wavelengths. Most reasonable interpretation of these results is that legibility tracked the sensitivity function of

Table 10. Analysis of Variance Summary Table for Display Legibility in 'Ocean' Turbidity

Source	df	MS	F	ω^2
Particle Concentration (C)	1	173.6111	<1	
Display Wavelength (W)	2	1336.9750	7.99**	.02
Display Size (D)	1	13838.3999	146.02**	.10
Display Luminance (L)	2	52582.6743	614.52**	.73
CW	2	315.4528	12.33**	
CD	1	2.1779	<1	
CL	2	32.9194	1.02	
WD	2	122.5748	5.74*	
WL	4	260.9500	7.50**	.01
DL	2	646.9746	10.54**	.01
CWD	2	73.3526	4.64*	
CWL	4	45.9111	3.76*	
CDL	2	23.9516	1.06	
WDL	4	22.4748	1.24	
CWDL	4	23.3020	2.05	

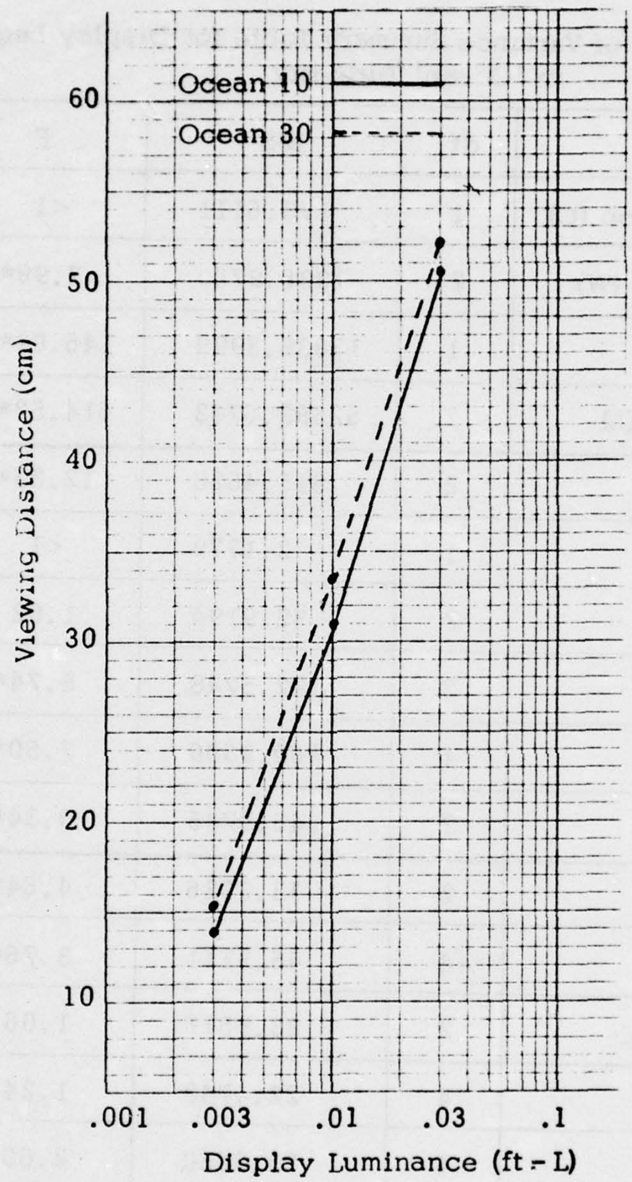


Figure 18. Maximum Legible Viewing Distance in Ocean Turbidity as a Function of Display Luminance

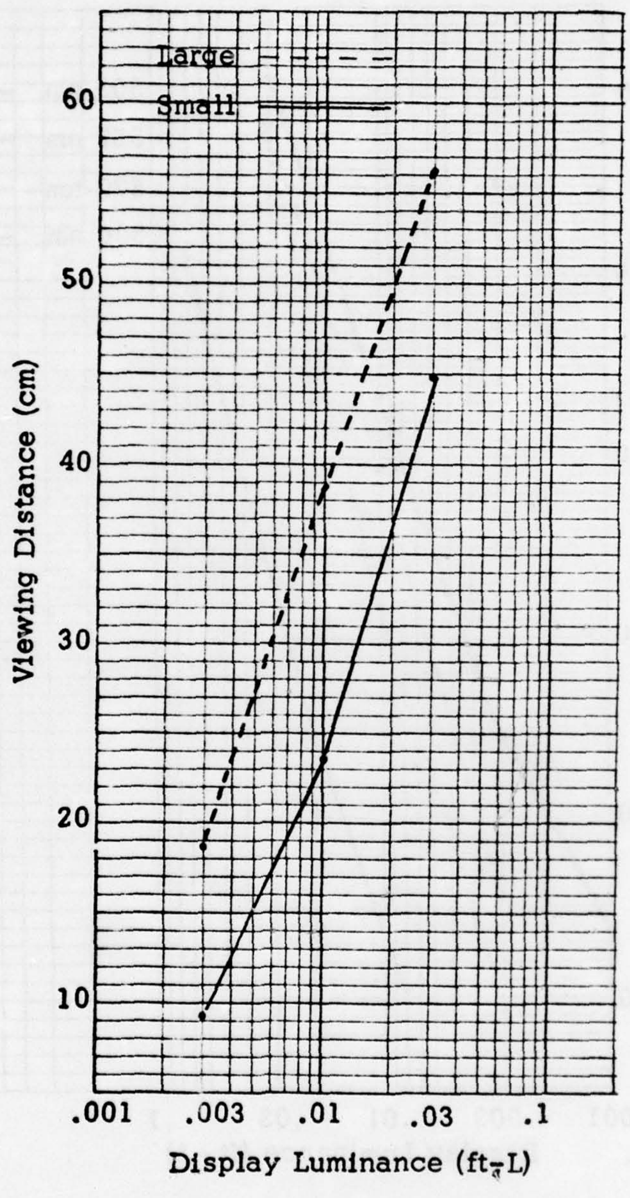


Figure 19. Maximum Legible Viewing Distance in Ocean Turbidity as a Function of Display Size

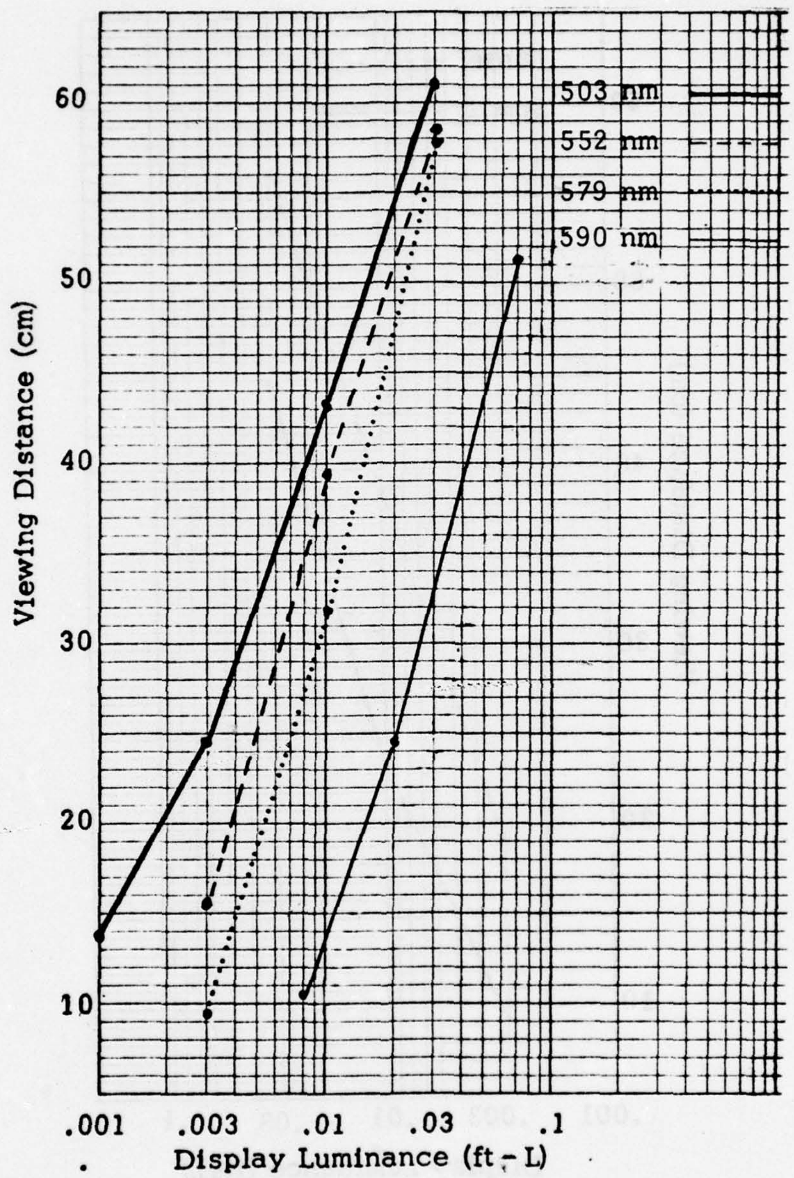


Figure 20. Maximum Legible Viewing Distance in Ocean Turbidity as a Function of Display Wavelength

rod-dominated vision. Table 11 shows the advantages of the shorter wavelengths when display luminance was measured using a scotopically corrected filter. At photopic values of .001 ft-L for example, the scotopic value of the 503 nm wavelength was .01 ft-L, while the scotopic value of 552 nm was .001 ft-L and the longer wavelengths were beyond the limits of scotopic measurement.

Table 11. Scotopic Luminance Values for Display Filter Conditions at Selected Photopic Levels
(Single filament bar; 6' spot)

Photopic Values (ft-L)	No Filter	579 nm Filter	552 nm Filter	503 nm Filter
.1	.03	.07	.24	2.50
.03	.01	.02	.06	.50
.01	.003	.007	.03	.16
.003	.001	.003	.008	.05
.001	--	--	.001	.01

IV. SUMMARY AND RECOMMENDATIONS

A. Latex Spheres Approximate Natural Turbidity

Use of latex spheres to simulate the optical and thereby perceptual effects of natural turbidity was initiated in the present research program with encouraging results. As a first effort, the simulation was limited to median particle sizes only; a more sophisticated effort would more closely approximate the known size distributions of natural water suspensoids. Even at this first level of simulation by median-sized particles, the optical effects were acceptable simulations of actual bay and harbor water samples. The 'Ocean' simulations were not validated, but their particle content was approximately one order of magnitude greater than known deep-ocean samples and their optical densities were only slightly greater than tap water; .10 to .15 log unit for the 'Ocean' simulations, .055 to .075 log unit for tap water. Oceanic water in the dark is not likely to be a problem for display legibility; at high ambient luminance levels, however, the question should be raised again.

The great advantage of the latex spheres lies in their sterility and settling characteristics by which a given turbidity condition can be prepared and maintained over time. Laboratory experimentation is far more efficient than experiments in natural waters, many options can be narrowed to a few promising alternatives in the laboratory for final selection in the field. The use of latex spheres enables an ambient viewing medium of known physical properties to be created and used for visual/perceptual experiments over a period of several weeks; furthermore, the same medium can be recreated in another laboratory or in another year for replications and extensions of earlier research.

B. Display Requirements for Legibility in Turbid Water Are Different than in Air

1. Viewing Distance

Display consoles in military aircraft are approximately 71 cm (28 inches) from the pilots' eyes. This distance most likely evolved as a design requirement based on the arm reach of the 5th percentile man (Woodson and Conover, 1966). Display characteristics were based on this constraint rather than a source of it.

Because of the turbidity of natural water environments, console design for ambient submersible vehicles must use display legibility as a primary constraint on eye-to-console distance; the closer the display the fewer particles in the visual pathway. A limiting condition on closeness is the accommodation near-point, the largest value of which in the present sample was 20 cm (8 inches). Based on the interaction of viewing distance and display luminance and given 20 cm as a lower limit, the range of 'comfortable' eye-to-console distances appears to be in the range of 25 to 50 cm (10-20 inches). In oceanic waters at these viewing distances, displays can be as dark as .01 to .03 ft-L; in turbid harbor water, display luminances in the range 1.0 to 1000 ft-L may be required.

2. Luminance

In numerous studies, measurements have been taken of the luminance of cockpit displays as set by operational Air Force and Navy pilots flying night missions (Cole, et al, 1950; Dohrn, 1967; Intano, 1967; DeBruine and Milligan, 1971). The average value of photopic luminance reported in these works has consistently been .03 ft-L and the ranges have been .01 to 0.1 ft-L. Furthermore, these values tend to be confirmed in laboratory research where dark-adapted subjects are able to control display luminance to a criterion of 'comfort' legibility (King, et al, 1970; Semple, et al, 1971; Johnson and Poston, 1976).

In the present experiments, ocean water as a viewing medium was similar to air regarding requirements for display luminance; a 0.03 ft-L display could be read at 50 cm (20 inches) and at .1 ft-L the 64 cm (25 inches) apparatus limit was exceeded. The harbor turbidity condition, however, required subtantially different luminance levels for legibility. In 'Harbor-10' turbidity a display luminance of .3 ft-L was required to be legible beyond the limits of accommodation and at 1000 ft-L, the display was legible at a maximum viewing distance of 61 cm (24 inches). In the more concentrated turbidity condition, Harbor-30, 100 ft-L was required to read the display at a distance barely beyond the limits of accommodation, 21 cm (8 inches) and at 1000 ft-L the maximum legible viewing distance was still only 25 cm (10 inches).

3. Size

Recommendations regarding display size for in-air applications are generally in the 20-30 minutes of visual angle range; the larger sizes appropriate to the poorer viewing conditions of luminance or contrast (Woodson and Conover, 1966; Grether and Baker, 1972). Results of experiments in display legibility suggest display sizes more on the order of 10-20 minutes visual angle (Reynolds, 1971; Carel, et al, 1974).

Viewed through the relatively clear water of the 'Ocean' simulations, the 4 mm display could be read legibly at a distance of 45 cm; the 8 mm display at 55 cm at display luminance of .03 ft-L. These combinations of size and viewing distances are 30 and 50 minutes of visual angle, respectively. In the more turbid water of Harbor-10 where values of display luminance to 1000 ft-L were included, the 4 mm display could be read at 60 cm and the larger 8 mm display at 63 cm: visual angles of 23 and 43 minutes. In the most turbid water, Harbor-30, at an identical luminance (1000 ft-L) legible display sizes were 55 and 110 minutes of visual angle.

As turbidity conditions worsened from Ocean-10 to Harbor-30, the contribution of display size to legibility progressively decreased. In the relatively clear water, the larger size display could be read 10 cm further than the small display at each comparable luminance level. This constant gain in legible viewing distance attributable to display size was reduced to 4 cm in Harbor-10 and to 1 cm in Harbor-30. For legibility in turbid water, displays need to subtend larger visual angles than required in-air, but the important factor in creating large visual angles is the reduction in viewing distance and not the increase in physical size of the display.

4. Wavelength

Wavelength or color typically is used in displays as a coding dimension and not as an aid to legibility. Also red light is often recommended for use in military display applications as a means of preserving dark adaptation, although the practical value of red as opposed to any other wavelength light at comparably low luminance is negligible (Luria and Kinney, 1967; Cavonius and Hilz, 1967; Reynolds, 1971; Johnson and Poston, 1976). In air, visual acuity is not generally regarded as wavelength dependent, although Reynolds, 1971, has reported evidence suggesting that, at large visual angles, display legibility is a function of wavelength in the order green, yellow, red.

Results of the present experiments suggest that given the combination of low levels of display luminance and large visual angles, dark adapted observers read displays according to the scotopic luminosity function, i.e., 505 nm (blue/green) was optimal for legibility. In the 'Ocean' turbidity simulation, i.e., relatively clear water, display luminance levels required for legibility were .1 ft-L and less, observers were presumably in a mesopic state of adaptation and the order of legibility as a function of wavelength was unambiguous in the order 503, 552, 579, 590 nanometers. In the 'Harbor-10' turbidity simulation the 503 nm wavelength (blue/green) was of superior legibility at luminances between .01 and .1 ft-L. At the level of turbidity

represented by Harbor-30 the legibility function was, for practical purposes, entirely accounted for by luminance.

In none of the display presentations below approximately .1 to .03 ft-L was a clear perception of 'color' experienced by observers. All display presentations appeared a neutral gray which supports the assumption that the observers were at least mesopically adapted.

C. Operational Applications with Qualifications

Results of the two experiments into the optimization of display characteristics for legibility in turbid water should provide some guidance to display design, however qualified.

Recalling the context of the experiments, the results have potential application only to self-luminous/transilluminated type of displays in support of a quantitative reading type of task, when the task is performed in a very dark ambient environment by a dark-adapted observer. Also, since these were experiments and not field tests, there are additional cautions. The observer had only one task to perform, read the 3-digit display, with no time constraint on that single, simple task. The task was a short-term effort not comparable, for example, to the continuous visual monitoring requirements of a submersible pilot. Finally, the criterion measured in the experiments was maximum legible viewing distance and not a measure of reading ease or comfort or speed.

Given the above conditions and cautions we believe it safe to conclude the following:

- For ambient console applications where long-duration continuous display monitoring is a requirement, design the console so that the operator can be comfortable at eye-to-console distances between 25 and 50 cm (10-20 inches). Closer than 25 cm viewing distances would help overcome the turbidity problem but would be fatiguing for the observer since the display would be too close to the limit of accommodation.

- At these relatively close viewing distances, 25-50 cm, displays do not have to be physically very large in size to subtend large visual angles. At a viewing distance of 25 cm, for example, a 4 mm display has a visual angle of 55 minutes.
- In relatively clear water, displays need only be as bright as 0.1 ft-L luminance.
- In turbid, harbor-type waters, however, the brighter the better. Viewing distance is a linear function of the logarithm of luminance and turbidity effects the slope of the function. Display luminance must be at least 100 ft-L and 1000 ft-L is preferable.
- At low levels of display luminance appropriate to clear water, 0.1 ft-L and less, make the display blue/green; i.e., use a filter or select a phosphor whose peak output is near 505 nm.
- At the high levels of display luminance needed for legibility in harbor-type of turbidity, variations in wavelength will not make a difference.

V. REFERENCES

Carel, W. L., Hershberger, M. L., Herman, J. A., and McGrath, J. J. Design criteria for airborne map displays. Volume I: Methodology and research results. Culver City: Hughes Aircraft Co., March 1974.

Cole, E. L., McIntosh, B. B., and Grether, W. F. Brightness levels of three instrument lighting systems used by pilots flying at night. Dayton, Ohio: Air Materiel Command, Wright-Patterson Air Force Base, August 1950.

Cavonius, C. R., and Hilz, R. Effect of chromatic light adaptation on visual performance. Bethesda, Md.: The Eye Research Foundation, August 1967.

DeBruine, D. J., and Milligan, J. R. In-flight test results on mission oriented cockpit requirements. Dayton, Ohio: Wright-Patterson Air Force Base, September 1971.

Dohrn, R. H. Luminance measurements for red and white-lighted aircraft instruments. In Aircraft instrument and cockpit lighting by red or white light. Paris, France: Advisory Group for Aerospace Research and Development, October 1967.

Grether, W. F., and Baker, C. A. Visual presentation of information. In H. P. VanCott and R. G. Kinkade (Eds.) Human engineering guide to equipment design, Revised Edition. Washington, D.C.: U.S. Government Printing Office, 1972.

Hays, W. L. Statistics for the social sciences. New York: Holt, Rinehart and Winston, Inc., 1973.

Intano, G. P. Legibility of various sized letters under aviation red, "lunar" white, and neutrally-filtered incandescent white lighting systems. In Aircraft instrument and cockpit lighting by red or white light. Paris, France: Advisory Group for Aerospace Research and Development, 1967.

James, H. R., and Birge, E. A. A laboratory study of the absorption of light by lake waters. Transactions Wisconsin Academy of Sciences, 31:1-154, 1938.

Jerlov, N. G. Optical oceanography. Amsterdam: Elsevier Publishing Company, 1968.

Johnson, N. A., and Poston, A. M. A comparison of red and white cockpit lighting under quasi-operational conditions. Aberdeen Proving Ground, Md.: U.S. Army Human Engineering Laboratory, January 1976.

Kent, P. R., and Weissman, S. Visual resolution underwater. Groton, Conn.: U.S. Naval Submarine Medical Center, Submarine Base, May 1966.

Ketchel, J. M., and Jenney, L. L. Electronic and optically generated aircraft displays. A study of standardization requirements. May 1968. AD 684 849.

King, R. C., Wollentin, R. W., Semple, C. A., Jr., Gottelmann, G. Electroluminescent display legibility research and development. Dayton, Ohio: Wright-Patterson Air Force Base, October 1970.

Kinney, J. A. S., Luria, S. M., and Weitzman, D. O. Visibility of colors underwater. J. opt. soc. Am., 1967, 57, 802-809.

Kinney, J. A. S., Luria, S. M., and Weitzman, D. O. Responses to the underwater distortions of visual stimuli. Groton, Conn.: U.S. Naval Submarine Medical Center, Submarine Base, July 1968.

Kinney, J. A. S., Luria, S. M., and Weitzman, D. O. Effect of turbidity on judgments of distance underwater. Percep. and motor Skills, 1969, 28, 331-333.

Kinney, J. A. S., McKay, C. L., Luria, S. M., and Gratto, C. L. The improvement of divers' compensation for underwater distortions. Groton, Conn.: U.S. Naval Submarine Medical Center, Submarine Base, 1970.

Luria, S. M. Stereoscopic acuity underwater. Groton, Conn.: U.S. Naval Submarine Medical Center, Submarine Base, February 1968.

Luria, S. M., Ferris, S. H., McKay, C. L., Kenney, J. A. S., and Paulson, H. M. Vision through various scuba facemasks. Groton, Conn.: U.S. Naval Submarine Medical Center, Submarine Base, December 1972.

Luria, S. M., and Kinney, J. A. S. Merits of red or white lighting for naval use. In Aircraft instrument and cockpit lighting by red or white light. Paris, France: Advisory Group for Aerospace Research and Development. October 1967.

Luria, S. M., Kinney, J. A. S., and Weissman, S. Estimates of size and distance underwater. Am. J. Psychol., 1967, 80(2), 282-286.

Meister, D., and Sullivan, D. J. Guide to human engineering design for visual displays. Canoga Park, Calif.: The Bunker-Ramo Corp., August 1969.

Poock, G. K. Underwater display visibility as influenced by turbidity, viewing distance, and color of illumination. Monterey, Calif.: Naval Postgraduate School, May 1972a.

Poock, G. K. Underwater display visibility as influenced by turbidity, display background color, and the color and intensity of illumination. Monterey, Calif.: Naval Postgraduate School, July 1972b.

Reynolds, H. N. The visual effects of exposure to electroluminescent instrument lighting. Human Factors, 1971, 13(1), 29-40.

Schubel, J. R. Size distributions of the suspended particles of the Chesapeake Bay turbidity maximum. Netherlands J. sea Res., 1969, 4, 283-309.

Schubel, J. R. Tidal variations of the size distribution of suspended sediment at a station in Chesapeake Bay turbidity maximum. Netherlands J. sea Res., 1971, 5, 252-266.

Schubel, J. R., Morrow, C. H., Cronin, W. B., and Mason, A. Suspended sediment data summary (Special Report 18). Chesapeake Bay Institute, 1970.

Semple, C. A., Jr., Heapy, R. J., Conway, E. R., Jr., and Burnette, K. T. Analysis of human factors data for electronic flight display systems. Dayton, Ohio: Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, April 1971.

Sheldon, R. W., Prakash, A., and Sutcliffe, W. H., Jr. The size distribution of particles in the ocean. Limnol. Oceanogr., 1972, 17, 327-340.

Stevens, S. S. Psychophysics. New York: John Wiley and Sons, 1975.

Vaughan, W. S., Jr., and Williams, J. An analysis of environmental and perceptual determinants of display legibility underwater. Landover, Md.: Oceanautics, Inc., April 1976.

Woodson, W. E., and Conover, E. W. Human engineering guide for equipment designers. (2nd ed.) Los Angeles: University of California Press, 1966.

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APPENDIX A

OPTICAL DENSITY VS WAVELENGTH FOR SAMPLES OF NATURALLY AND ARTIFICIALLY TURBID WATER

Table A-1. Optical Density of Harbor-10 Simulation

Wavelength (nm)	Time Samples		Mean
	15 April 76	13 May 76	
500	.9353	.5605	.7479
503	.9358	.5594	.7476
510	.9211	.5563	.7387
520	.9171	.5527	.7349
530	.9055	.5470	.7263
540	.9031	.5391	.7211
550	.8856	.5356	.7106
555	.8856	.5312	.7084
560	.8762	.5243	.7003
570	.8565	.5195	.6880
579	.8534	.5110	.6822
590	.8302	.5091	.6697
600	.8234	.4984	.6609

Table A-2. Optical Density of Harbor-30 Simulation

Wavelength (nm)	Time Samples					Mean	S.D.
	25 May 76	2 June 76	4 June 76	8 June 76	11 June 76		
500	1.5370	1.7210	1.6020	1.6200	1.3980	1.5756	.1192
503	1.5530	1.7220	1.6200	1.6200	1.3870	1.5804	.1238
510	1.5630	1.6990	1.6200	1.6200	1.3770	1.5758	.1212
520	1.5090	1.7210	1.5850	1.6200	1.3470	1.5564	.1397
530	1.5080	1.6980	1.5840	1.6190	1.3550	1.5528	.1300
540	1.5090	1.6780	1.6020	1.6200	1.3470	1.5512	.1293
550	1.4940	1.6770	1.5850	1.5850	1.3370	1.5356	.1285
555	1.4940	1.6570	1.5680	1.5680	1.3270	1.5228	.1238
560	1.4950	1.6780	1.5530	1.5530	1.3280	1.5214	.1271
570	1.4680	1.6380	1.5220	1.5520	1.3090	1.4978	.1222
579	1.4550	1.6020	1.4940	1.5370	1.3010	1.4778	.1129
590	1.4320	1.6030	1.4820	1.5230	1.2850	1.4650	.1185
600	1.4310	1.6020	1.4810	1.4940	1.2670	1.4550	.1222

Table A-3. Optical Density of Ocean-10 Simulation

Wavelength (nm)	Time Samples				Mean	S.D.
	28 June 76	2 July 76	6 July 76	14 July 76		
500	.1597	.1461	.1473	.1528	.1515	.0062
503	.1564	.1454	.1454	.1503	.1494	.0052
510	.1546	.1400	.1430	.1454	.1458	.0063
520	.1486	.1336	.1366	.1396	.1396	.0065
530	.1422	.1273	.1308	.1338	.1335	.0064
540	.1391	.1244	.1290	.1302	.1307	.0061
550	.1344	.1181	.1216	.1233	.1244	.0070
555	.1303	.1141	.1210	.1193	.1212	.0068
560	.1302	.1146	.1169	.1192	.1202	.0069
570	.1250	.1096	.1136	.1130	.1153	.0067
579	.1227	.1057	.1091	.1085	.1115	.0076
590	.1197	.1029	.1067	.1062	.1089	.0074
600	.1147	.0991	.1030	.1002	.1043	.0072

Table A-4. Optical Density of Ocean-30 Simulation

Wavelength (nm)	Time Samples			Mean	S.D.
	18 June 76	22 June 76	25 June 76		
500	.1547	.1449	.1836	.1611	.0201
503	.1552	.1436	.1834	.1607	.0205
510	.1509	.1388	.1775	.1557	.0198
520	.1456	.1348	.1725	.1510	.0194
530	.1422	.1303	.1664	.1463	.0184
540	.1379	.1249	.1612	.1413	.0184
550	.1344	.1198	.1550	.1364	.0177
555	.1332	.1187	.1544	.1354	.0180
560	.1302	.1163	.1500	.1322	.0169
570	.1273	.1113	.1464	.1283	.0176
579	.1244	.1074	.1410	.1243	.0168
590	.1197	.1067	.1384	.1216	.0159
600	.1181	.1019	.1338	.1179	.0160

Table A-5. Optical Density of Chesapeake Bay Water Samples at the Surface

Wavelength (nm)	Sample 1	Sample 2	Sample 3	Mean
500	.2557	.4762	.2924	.3414
503	.2518	.4685	.2890	.3364
510	.2480	.4609	.2823	.3304
520	.2403	.4547	.2716	.3222
530	.2366	.4425	.2636	.3142
540	.2292	.4330	.2589	.3070
550	.2233	.4225	.2526	.2995
555	.2219	.4202	.2503	.2975
560	.2197	.4145	.2487	.2943
570	.2147	.4067	.2411	.2875
579	.2090	.4012	.2366	.2823
590	.2069	.3958	.2314	.2780
600	.2027	.3872	.2262	.2720

Table A-6. Optical Density of Chesapeake Bay Water Samples at 5 Meters

Wavelength (nm)	Sample 1	Sample 2	Mean
500	.4449	.5719	.5084
503	.4437	.5686	.5062
510	.4377	.5575	.4976
520	.4306	.5500	.4903
530	.4179	.5376	.4778
540	.4089	.5229	.4659
550	.3979	.5115	.4547
555	.3872	.5086	.4479
560	.3799	.5072	.4436
570	.3768	.4949	.4359
579	.3615	.4841	.4228
590	.3536	.4750	.4143
600	.3458	.4685	.4072

Table A-7. Optical Density of Chesapeake Bay Water Samples Near the Bottom (13 Meters)

Wavelength (nm)	Sample 1	Sample 2	Mean
500	.9208	1.319	1.1199
503	.9208	1.310	1.1154
510	.9101	1.292	1.1011
520	.8861	1.259	1.0726
530	.8570	1.229	1.0430
540	.8539	1.194	1.0240
550	.8300	1.168	.9990
555	.8239	1.155	.9895
560	.8182	1.149	.9836
570	.8041	1.125	.9646
579	.7905	1.108	.9493
590	.7747	1.086	.9304
600	.7670	1.066	.9165

Table A-8. Optical Density of Baltimore Harbor Water at the Bottom

Wavelength (nm)	Sample 1
500	3.893
503	3.872
510	3.819
520	3.737
530	3.665
540	3.605
550	3.526
555	3.468
560	3.439
570	3.372
579	3.298
590	3.233
600	3.188

APPENDIX B

CALIBRATIONS

CALIBRATIONS

A. Description of Color by the C.I.E. System[1]

The following is the procedure by which the chromaticities of (pin-light) alpha-numeric displays in the present experiment were computed by first computing the tristimulus values of the light as follows:

$$X = \sum_{\lambda_1}^{\lambda_n} t_\lambda H_\lambda \bar{x}_\lambda (\Delta\lambda) \qquad \text{(B.1)}$$

$$Y = \sum_{\lambda_1}^{\lambda_n} t_\lambda H_\lambda \bar{y}_\lambda (\Delta\lambda) \qquad \text{(B.2)}$$

$$Z = \sum_{\lambda_1}^{\lambda_n} t_\lambda H_\lambda \bar{z}_\lambda (\Delta\lambda) \qquad \text{(B.3)}$$

Note: $\Delta\lambda$ is cancelled out in our computations since $\Delta\lambda$ = constant where:

λ_{nm} = wavelength in nanometers

t_λ = transmission by wavelength

H_λ = relative spectral radiance emittance of a blackbody radiator at 1700°K (Mfg. measurement of color temperature of alpha-numeric displays used in present experiment)

$\left.\begin{array}{l}\bar{x}_\lambda \\ \bar{y}_\lambda \\ \bar{z}_\lambda\end{array}\right\}$ = spectral tristimulus values of equal energy spectrum, 1931 C.I.E. standard observer, 2° field.

Following this calculation, the chromaticity coefficients x, y, and z were computed by the following:

$$x = \frac{X}{X + Y + Z} \qquad \text{(B.4)}$$

[1] For a more detailed explanation of the C.I.E. System see — Nimeroff, I. Colorimetry. National Bureau of Standards Monography 104. Washington, D.C.: U.S. Government Printing Office, 1968.

$$y = \frac{Y}{X + Y + Z} \qquad (B.5)$$

$$z = \frac{Z}{X + Y + Z} \qquad (B.6)$$

These values are used to compute the coordinates of each filter-light combination so as to specify their location in the 1931 C.I.E. chromaticity diagram, for comparison with other signal lights. The location x, y within the C.I.E. diagram helps to specify the dominant wavelength and purity of a signal color.

In general, the spectral energy distribution of light shining in the eye will determine the "color" of the light. However, the reverse is not true, that is, two lights may be the same in color perceptually, but may differ widely in their spectral composition. Therefore, in order to accurately specify the colors of lights, a uniform system called colorimetry was developed. This system was developed as a physical means of describing stimuli for color vision, using as a reference, internationally standardized values of generalized characteristics for the vision of an average observer.

Figure 2, Section II, shows the color mixture diagram according to the 1931 C.I.E. standard observer and coordinate system. In general, a value located on the perimeter of the diagram indicates a 100% saturated spectral color. Values located toward the internal center of the diagram, tend to be desaturated with "pure white light" located in the region marked "Standard C".

1. Computation of Chromaticity Coefficients

In order to describe the colors used in the present experiment, the C.I.E. system of color notation was used.

All viewing conditions used a tungsten 1700°K alpha-numeric display. Table B-1 shows the relative energy by wavelength for a 1700°K source.[1]

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[1] Pivovonsky, M., and Nagel, M. R. Tables of Blackbody Radiation Functions. New York: Macmillan Company, 1961.

Table B-1. Relative Energy of A Blackbody Radiator at 1700°K

λ_{nm}	1700°K H_λ	λ_{nm}	1700°K H_λ
430	23.19	530	333.53
435	27.44	535	369.43
440	32.32	540	408.23
445	37.91	545	450.10
450	44.28	550	495.17
455	51.51	555	543.59
460	59.70	560	59[illegible].52
465	68.92	565	651.10
470	79.28	570	710.48
475	90.88	575	773.80
480	103.82	580	841.22
485	118.22	585	912.86
490	134.19	590	988.87
495	151.84	600	1154.60
500	171.31	610	1339.40
505	192.72	620	1544.30
510	216.20	630	1770.20
515	241.88	640	2018.10
520	269.90	650	2288.70
525	300.40		

Table B-2 shows the percent transmittance by wavelength for each interference filter used in the present experiment.

Table B-2. Transmittance vs Wavelength for the Three Interference Filters

Filter No. 503		Filter No. 552		Filter No. 579	
λ_{nm}	t_λ = % Transmitted	λ_{nm}	t_λ = % Transmitted	λ_{nm}	t_λ = % Transmitted
430	0.00	440	0.00	545	0.00
440	0.50	450	0.50	550	0.75
450	0.75	460	0.50	555	1.00
460	1.00	470	0.50	560	1.50
470	1.50	480	0.50	565	3.00
480	3.00	490	0.60	570	11.00
490	13.00	500	0.75	575	37.00
500	40.00	510	0.80	580	25.00
510	11.00	520	1.00	585	5.00
520	3.00	530	3.00	590	2.00
530	1.00	540	8.00	595	0.00
540	0.00	550	37.50		
		560	5.50		
		570	1.00		
		580	0.50		
		590	0.00		

Table B-3 shows the computations necessary for specifying the chromaticity of the three colored filters in the present experiment when viewed through a 1700°K source.

The coordinates of the three colored displays and the "bare bulb" display used in this experiment are:

Filter No. 503: x = .0350
y = .5382

Filter No. 552: x = .3038
y = .6813

Filter No. 579: x = .4880
y = .5110

Bare Alpha Numeric Display at 1700°K:[1] x = .5610
y = .4043

Pure White Light - "daylight" or Standard C: x = .3101
y = .3163

A calibration for each filter used in the present experiment was performed by comparing the transmittance of each filter at 10 nm intervals throughout the visible spectrum. For the interference filters Figure B-1 shows the transmittance times the relative energy of a typical 1700°K source for white light (1700°K) and for each of the three filters, numbered 503, 552, and 579 (Note: Filter numbers are their nominal peak wavelength).

2. Calibration of Neutral Density Filters

Neutral density filters (Fish-Shurman) were calibrated by placing them in front of a photomultiplier (Spectra-Pritchard Model 1980 Digital Photometer) which is aimed at a uniform light source. The relative amount of light transmitted is then recorded for each chromatic filter combination.

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[1] Wyzecki, G., and Stiles, W. S. Color Science: Concepts and Methods, Quantitative Data and Formulas. New York: Wiley and Sons, 1967.

Table B-3. Calculation of Chromaticity Coordinates – Filter No. 503 - 1700°K Source

λ_{nm}	t_λ	H_λ $t_\lambda H_\lambda$	$\bar{x}_\lambda$	$t_\lambda H_\lambda \bar{x}_\lambda$	$\bar{y}_\lambda$	$t_\lambda H_\lambda \bar{y}_\lambda$	$\bar{z}_\lambda$	$t_\lambda H_\lambda \bar{z}_\lambda$
430	0.00	$2.3186 \times 10^1 = 0.00$	.2839	0.0000	.0116	0.0000	1.3856	0.0000
440	0.50	$3.2320 \times 10^1 = 16.160$	.3483	5.6285	.0230	.3717	1.7471	28.2331
450	0.75	$4.4280 \times 10^1 = 33.210$	.3362	11.1652	.0380	1.2620	1.7721	58.8514
460	1.00	$5.9697 \times 10^1 = 59.697$	.2908	17.3599	.0600	3.5818	1.6692	99.6462
470	1.50	$7.9282 \times 10^1 = 118.923$	.1954	23.2376	.0910	10.8220	1.2876	153.1253
480	3.00	$1.0382 \times 10^2 = 311.460$	.0956	29.7756	.1390	43.2929	.8130	253.2170
490	13.00	$1.3419 \times 10^2 = 1744.470$	.0320	55.8230	.2080	362.8498	.4652	811.5274
500	40.00	$1.7131 \times 10^2 = 6852.400$	.0049	33.5768	.3230	2213.3252	.2720	1863.8528
510	11.00	$2.1620 \times 10^2 = 2378.200$	.0093	22.1173	.5030	1196.2346	.1582	376.2312
520	3.00	$2.6990 \times 10^2 = 809.700$	.0633	51.2540	.7100	574.8870	.0782	63.3185
530	1.00	$3.3353 \times 10^2 = 333.530$	.1655	55.1992	.8620	287.5029	.0422	14.0750
540	0.00	$4.0823 \times 10^2 = 0.000$	.2904	0.0000	.9540	0.0000	.0203	0.0000

$$X = \sum_{\lambda=430}^{\lambda=540} t_\lambda H_\lambda \bar{x}_\lambda$$

X = 305.1400 Y = 4694.1300 Z = 3722.0800

$$x = \frac{X}{X+Y+Z} = \frac{305.14}{8721.34} = .0350 \qquad z = \frac{Z}{X+Y+Z} = \frac{3722.08}{8721.34} = .4268$$

$$y = \frac{Y}{X+Y+Z} = \frac{4694.13}{8721.34} = .5382 \qquad z = \frac{z}{x+y+z} = \frac{127.35}{119148.43} = .0010$$

λ_{nm} = wavelength in nanometers

t_λ = transmission by wavelength

H_λ = relative spectral radiance emittance of a blackbody radiator at 1700°K

$\bar{x}_\lambda$ = spectral tristimulus values of equal

$\bar{y}_\lambda$ = energy spectrum 1931 C.I.E.

$\bar{z}_\lambda$ = standard observer, 2° field

Table B-3. Calculation of Chromaticity Coordinates – Filter No. 552 - 1700°K Source (Continued)

λ_{nm}	t_λ	H_λ	$t_\lambda H_\lambda$	$\bar{x}_\lambda$	$t_\lambda H_\lambda \bar{x}_\lambda$	$\bar{y}_\lambda$	$t_\lambda H_\lambda \bar{y}_\lambda$	$\bar{z}_\lambda$	$t_\lambda H_\lambda \bar{z}_\lambda$
440	0.00	3.2320×10^1	= 0.00	.3483	0.000	.0230	0.000	1.7471	0.000
450	0.50	4.4280×10^1	= 22.14	.3362	7.443	.0380	.841	1.7721	39.234
460	0.50	5.9697×10^1	= 29.85	.2908	8.680	.0600	1.791	1.6692	49.823
470	0.50	7.9280×10^1	= 39.64	.1954	7.746	.0910	3.607	1.2876	51.040
480	00.50	1.0382×10^2	= 51.91	.0956	4.963	.1390	7.215	.8130	42.203
490	0.60	1.3419×10^2	= 80.51	.0320	2.576	.2080	16.747	.4652	37.455
500	0.75	1.7131×10^2	= 128.48	.0049	.630	.3230	41.500	.2720	34.455
510	0.80	2.1620×10^2	= 172.96	.0093	1.609	.5030	86.999	.1582	27.362
520	1.00	2.6990×10^2	= 269.90	.0633	17.085	.7100	191.629	.0782	21.106
530	3.00	3.3353×10^2	= 1000.59	.1655	165.598	.8620	862.509	.0422	42.225
540	8.00	4.0823×10^2	= 3265.84	.2904	948.400	.9540	3115.611	.0203	66.297
550	37.50	4.9517×10^2	= 18568.875	.4334	8047.750	.9950	18476.031	.0087	161.549
560	5.50	5.9552×10^2	= 3275.36	.5945	1947.202	.9950	3258.983	.0039	12.774
570	1.00	7.1048×10^2	= 710.48	.7621	541.457	.9520	676.377	.0021	1.492
580	.50	8.4122×10^2	= 420.61	.9163	385.405	.8700	365.931	.0017	.715
590	0.00	9.8887×10^2	= 0.00	1.0263	0.000	.7570	0.000	.0011	0.000

X = 12086.544   Y = 27105.770   Z = 588.22

$$x = \frac{X}{X+Y+Z} = \frac{12086.544}{39780.5360} = .3038 \qquad y = \frac{Y}{X+Y+Z} = \frac{27105.770}{39780.5360} = .6814 \qquad z = \frac{Z}{X+Y+Z} = \frac{588.220}{39780.5360} = .0148$$

Table B-3. Calculation of Chromaticity Coordinates — Filter No. 579 - 1700°K Source (Continued)

λ_{nm}	t_λ	H_λ	$t_\lambda H_\lambda$	$\bar{x}_\lambda$	$t_\lambda H_\lambda \bar{x}_\lambda$	$\bar{y}_\lambda$	$t_\lambda H_\lambda \bar{y}_\lambda$	$\bar{z}_\lambda$	$t_\lambda H_\lambda \bar{z}_\lambda$
545	0.00	4.501×10^2 =	0.00	.3597	0.00	.9803	0.00	.0134	0.00
550	0.75	4.9517×10^2 =	371.38	.4334	160.96	.9950	369.52	.0087	3.23
555	1.00	5.4359×10^2 =	543.59	.5121	278.37	1.0002	543.70	.0057	3.10
560	1.50	5.9552×10^2 =	893.28	.5945	531.05	.9950	888.81	.0039	3.48
565	3.00	6.5110×10^2 =	1953.30	.6784	1325.12	.9786	1911.50	.0027	5.27
570	11.00	7.1048×10^2 =	7815.28	.7621	5956.02	.9520	7440.15	.0021	16.41
575	37.00	7.7380×10^2 =	28630.60	.8425	24121.28	.9154	26208.45	.0018	51.54
580	25.00	8.4122×10^2 =	21030.50	.9163	19270.25	.8700	18296.54	.0017	35.75
585	5.00	9.1286×10^2 =	4564.30	.9786	4466.62	.8163	3725.84	.0014	6.39
590	2.00	9.8887×10^2 =	1977.74	1.0263	2029.75	.7570	1497.15	.0011	2.18
595	0.00	0.0	0.0	1.0567	0.00	.6949	0.00	.0010	0.00

X = 58139.42   Y = 60881.66   Z = 127.35

$$X = \sum_{\lambda=545}^{\lambda=595} t_\lambda H_\lambda \bar{x}_\lambda \qquad Y = \sum_{\lambda=545}^{\lambda=595} t_\lambda H_\lambda \bar{y}_\lambda \qquad Z = \sum_{\lambda=545}^{\lambda=595} t_\lambda H_\lambda \bar{z}_\lambda$$

$$x = \frac{X}{X+Y+Z} = \frac{58139.42}{58139.42 + 60881.66 + 127.35} = \frac{58139.42}{119148.43} = .49$$

$$y = \frac{Y}{X+Y+Z} = \frac{50883.25}{119148.43} = .51$$

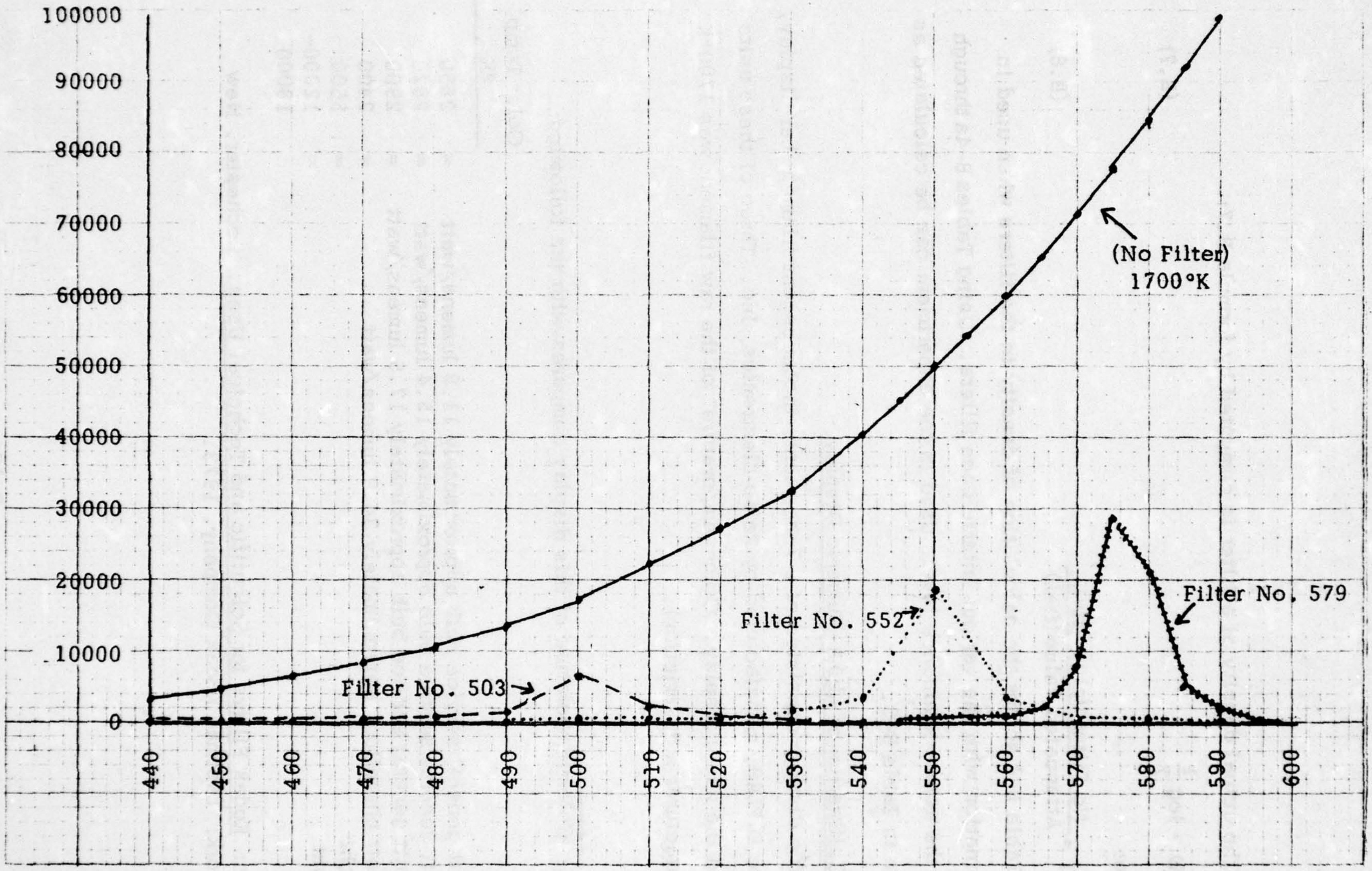

Figure B-1. Relative Energy Distribution of the Experimental Conditions

The actual density of a filter is computed by formula B.7:

$$D = \log \frac{1}{T} \qquad (B.7)$$

where:

$$T = \frac{\text{No Filter Value (ft-L)}}{\text{Attenuated Value (ft-L)}} \qquad (B.8)$$

Table B-4 shows the calculation of density in the filters when used in combination with the various interference filters. Using Tables B-4a through B-4c the actual luminance levels used in the experiment can be calculated as shown in Table B-5.

B. Calibration of Alpha-Numeric Display

The display consisted of a 7-segment, incandescent filament bar display, Pinlite DIP640, manufactured by Refac Electronics, Inc. Three of these units formed the basic display. Color temperature* of the raw filament was 1700°K (manufacturer's description).

---

*Note: Color temperature of this display compares with the following:

		Color Temp. °K
40 watt general service bulb approximately 11.8 lumens/watt	=	2650
75 watt general service bulb approximately 15.4 lumens/watt	=	2820
100 watt general service bulb approximately 17.5 lumens/watt	=	2900
500 watt photoflood approximately 34.0 lumens/watt	=	3400
Daylight	=	5500
Skylight	=	12000-18000

Source: Kodak Filters for Scientific and Technical Uses. Rochester, New York: Eastman Kodak Company, 1973.

Table B-4a. Calibration at 503 nm (at 7.63 ft-L)

Nominal Density (Log Units)	Ft-L Measured	T	Actual Density (Log Units) When Used with 503 Filter
4.0	.003	Log 2543	3.41
3.0	.007	Log 1090	3.04
2.0A	.060	Log 127.17	2.10
2.0B	.055	Log 138.73	2.14
1.0A	.600	Log 12.72	1.10
1.0B	.600	Log 12.72	1.10
0.7	1.800	Log 4.24	0.63
0.5A	1.800	Log 4.24	0.63
0.5B	1.900	Log 4.02	0.60
0.4	2.350	Log 3.25	0.51
0.3A	2.710	Log 2.82	0.45
0.3B	2.940	Log 2.60	0.41

Table B-4b. Calibration at 552 nm (at 32.0 ft-L)

Nominal Density (Log Units)	Ft-L Measured	T	Actual Density (Log Units) When Used with 552 Filter
4.0	.003	Log 10667	4.03
3.0	.030	Log 1067	3.03
2.0A	.210	Log 152.38	2.18
2.0B	.200	Log 160.00	2.20
1.0A	2.410	Log 13.28	1.12
1.0B	2.410	Log 13.28	1.12
.7	3.600	Log. 8.89	0.95
.5A	7.000	Log 4.57	0.66
.5B	7.35	Log 4.35	0.64
.4	99.35	Log 3.42	0.53
.3A	11.80	Log 2.71	0.43
.3B	11.65	Log 2.75	0.44

Table B-4c. Calibration at 579 nm (at 34.0 ft-L)

Normal Density	ft-L Measured	T	Actual Density (Log Units) When Used with 579 Filter
4.0	.003	Log 11333	4.05
3.0	.025	Log 1360	3.13
2.0A	.230	Log 147.83	2.17
2.0B	.240	Log 141.67	2.15
1.0A	2.670	Log 12.73	1.10
1.0B	2.500	Log 13.60	1.13
.7	3.800	Log 8.95	0.95
.5A	7.660	Log 4.44	0.65
.5B	7.900	Log 4.30	0.63
.4	10.200	Log 3.33	0.52
.3A	12.850	Log 2.65	0.42
.3B	13.200	Log 2.58	0.41

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LEGIBILITY OF SELF-LUMINOUS DISPLAY VARIATIONS VIEWED THROUGH A--ETC(U)
AUG 77 W S VAUGHAN, R A GLASS, J WILLIAMS N00014-74-C-0276
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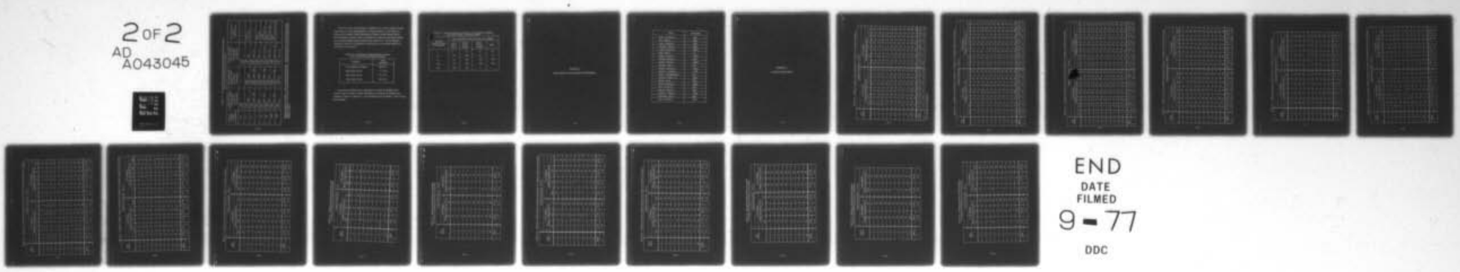

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Table B-5. Luminance and Filter Combinations for Experimental Conditions
(Exact filter designations in parenthesis)

Nominal Luminance Levels (Ft-Lamberts)	Actual Luminance* Level with "Yellow" 579 nm Filter at 34.0 ft-L (Ft-Lamberts)	Actual Luminance* Level with "Green" 552 nm Filter at 32.0 ft-L (Ft-Lamberts)	Actual Luminance* Level with "Blue" 503 nm Filter at 7.63 ft-L (Ft-Lamberts)	Actual Luminance* Level Clear Display
3.0	2.520 (1.0)	--	2.968 (.3B)	--
1.0	0.761 (.4 + 1.0B)	0.881 (.3B + 1.0A)	1.053 (.3A + .3B)	1.000 (.3 + 3.0)
.3	0.178 (.4 + 1.0B + .5B)	0.193 (.3B + 1.0A + .5A)	0.265 (.3A + .3B + .5)	--
.1	0.073 (.4 + 2.0)	0.077 (.3B + 2.0A)	0.247 (.3A + .3B + .7)	0.073 (.3 + 4.0)
.03	0.017 (.4 + 2.0 + .5B)	0.017 (.3B + 2.0A + .5A)	0.021 .3A + .3B + 1.0 +.5)	0.020 (.3 + 4.0 + .5)
.01	0.008 (.4 + 3.0)	0.011 (.3B + 3.0)	0.008 (.3A + .3B + 2.0)	0.008 (.3 + 4.0 + 1.0)
.003	0.002 (.4 + 3.0 + .5B)	0.002 (.3B + 3.0 + .5A)	0.002 (.3A + .3B + 2.0 + .5)	0.002 (.3 + 4.0 + 1.0 + .5)
.001	0.001 (.4 + 4.0)	0.001 .3B + 4.0)	0.001 (.3A + .3B + 3.0)	--

*Values computed as follows: Sum all neutral density filters. Find antilog of value, then take the inverse. Multiply result by the maximum luminance (ft-Lamberts) with interference filter in place (no neutral density filters in place).

Table B-6 shows the photometric calibrations of a typical numeric display when using a 2' spot superimposed on a single filament, and the effect of adding each chromatic filter separately and without neutral density filters. This information was then used to calculate the neutral density filters needed for the several experimental conditions (see Table B-5). For the effective intensity in terms of the adaptation state of the eye, the reader should consult Table 5 in Section II.

Table B-6. Luminance of Alpha-Numeric Display with 2 Min-Arc Spot on Single Filament

Condition	Total Luminance
Raw Display (no filters)	1800 ft-L
With Filter 503 nm	7.6 ft-L
With Filter 552 nm	32.0 ft-L
With Filter 579 nm	34.0 ft-L

Since some conditions are at extremely low levels the photopic foot-Lambert values in Table B-5 were recomputed by measuring in scotopic foot-Lamberts as shown in Table B-7. The raw display with no filters = 1200 scotopic foot-Lamberts.

Table B-7. Actual Luminance in Scotopic Foot-Lamberts Compared to Nominal Photopic Luminance Values

Nominal Photopic Values (Ft-Lamberts)	Actual Luminance Level (Scotopic ft-L Values)			
	Filter 503 nm "Blue"	Filter 552 nm "Green"	Filter 579 nm "Yellow"	Clear
.1	2.5	.24	.07	.03
.03	.50	.064	.02	.01
.01	.16	.026	.007	.003
.003	.05	.008	.003	.001
.001	.014	.001	--	--

APPENDIX C

PARTICIPANTS IN THE LEGIBILITY EXPERIMENTS

Name	Rank/Rate
Brown, William H.	HT2
Carl, Keith P.	ENS.
Caron, Ronald B.	BM2
Cormier, Craig D.	QM2
Cozart, Jerome D.	BMCS
Dew, John R.	LT
Dilley, James R.	LT(jg)
Findlay, Ronald A.	RM2
Hacker, Ernest C.	GMGC
Hanrath, Tom C.	AT3
Haskin, Herbert C.	GMC1
Hawkins, Thomas L.	LCDR
Kellas, Christropher D.	EN1
Lapping, Harold, Jr.	MMC
Martin, Pat G.	BMC
Power, Wheeler D.	BMCS
Ross, Ronald W.	BM2
Rowley, Daniel L.	EM2
Simmons, Larry W.	LT(jg)
Soderberg, John A.	BM1
Yates, George E.	QM2

APPENDIX D

LEGIBILITY DATA TABLES

Table D-1. Maximum Legible Viewing Distances for Harbor-10 Turbidity Condition

Test Divers	Display Wavelength: 503 nm											
	4 mm Display						8 mm Display					
	Display Luminance (ft-L)						Display Luminance (ft-L)					
	.01	.03	.1	.3	1.0	10	.01	.03	.1	.3	1.0	10
1	8*	10	15	16	22	28	10	9	20	24	28	30
2	16	19	23	26	33	39	20	22	27	30	40	43
3	18	22	27	26	26	38	20	25	26	34	36	45
4	6	16	21	22	27	34	12	15	25	27	32	39
5	9	15	22	21	26	32	13	17	24	27	32	41
6	7	12	19	21	28	35	6	14	26	26	33	38
7	6	16	23	25	30	39	11	14	24	27	30	37
8	11	15	23	26	29	37	17	20	31	30	34	45
9	9	13	17	19	25	32	12	14	27	21	24	35
10	16	20	26	30	31	41	21	25	33	34	41	49
11	17	24	32	31	37	44	20	29	38	33	42	48
Mean	11.18	16.55	22.55	23.91	28.55	36.27	14.73	18.55	27.36	28.45	33.82	40.91
σ	4.67	4.30	4.74	4.57	4.13	4.61	5.08	6.12	4.95	4.18	5.60	5.79

*Cell entries are centimeters.

Table D-1. Maximum Legible Viewing Distances for Harbor-10 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 552 nm													
	4 mm Display							8 mm Display						
	Display Luminance (ft-L)							Display Luminance (ft-L)						
	.01	.03	.1	.3	1.0	10	30	.01	.03	.1	.3	1.0	10	30
1	5	7	13	18	24	36	38	11	10	13	23	29	34	41
2	5	12	18	24	30	42	46	8	16	22	29	39	50	50
3	8	10	15	22	28	39	43	16	22	26	32	38	45	50
4	5	7	13	20	28	40	44	9	13	17	25	32	44	47
5	5	11	16	20	25	37	40	10	14	18	25	33	42	45
6	6	9	16	22	28	40	43	5	13	19	27	33	44	46
7	11	16	19	27	32	44	45	11	18	26	25	36	44	49
8	5	6	14	17	26	37	43	7	13	19	25	33	42	48
9	9	12	17	25	28	39	43	9	13	19	27	30	43	47
10	8	11	18	23	31	42	46	14	15	22	31	37	46	51
11	8	15	24	28	33	44	49	15	19	27	31	40	49	53
Mean	6.82	10.55	16.64	22.36	28.45	40.00	43.64	10.45	15.09	20.73	27.27	34.55	43.91	47.91
σ	2.09	3.21	3.17	3.50	2.84	2.76	2.98	3.42	3.42	4.34	3.04	3.67	4.18	3.27

Table D-1. Maximum Legible Viewing Distances for Harbor-10 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 579 nm													
	4 mm Display Display Luminance (ft-L)							8 mm Display Display Luminance (ft-L)						
	.01	.03	.1	.3	1.0	10	30	.01	.03	.1	.3	1.0	10	30
1	5	7	12	18	22	38	42	5	18	16	20	26	40	45
2	5	9	14	22	30	41	46	6	10	20	24	32	47	52
3	5	6	16	22	26	40	44	12	16	21	31	38	46	50
4	5	9	13	21	28	43	46	5	9	17	25	31	47	50
5	6	9	16	20	26	42	47	5	6	11	20	23	39	43
6	5	7	12	18	26	41	45	5	8	15	22	29	43	47
7	8	15	20	26	32	43	46	9	14	20	26	35	46	49
8	5	6	10	16	24	37	43	5	6	13	24	30	40	48
9	5	10	15	21	27	43	47	8	13	20	26	32	45	49
10	5	11	18	23	31	43	47	9	14	20	27	33	47	51
11	6	10	21	21	32	45	50	10	12	20	28	37	49	55
Mean	5.45	9.00	15.18	20.73	27.64	41.45	45.73	7.18	11.45	17.55	24.82	31.45	44.45	49.00
σ	.93	2.61	3.46	2.72	3.29	2.38	2.20	2.52	3.98	3.39	3.34	4.46	3.42	3.29

Table D-1. Maximum Legible Viewing Distances for Harbor-10 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 590 nm									
	4 mm Display					8 mm Display				
	Display Luminance (ft-L)					Display Luminance (ft-L)				
	1	10	30	100	1000	1	10	30	100	1000
1	20	32	36	41	56	18	33	40	46	57
2	18	38	44	51	64	24	44	49	56	64
3	20	34	40	45	58	23	40	46	52	64
4	24	37	43	49	64	25	38	46	54	64
5	13	34	39	46	59	15	36	42	51	64
6	20	34	35	44	57	20	37	42	49	63
7	20	38	44	49	64	20	40	46	53	64
8	19	33	40	49	60	25	38	46	53	61
9	20	37	41	50	59	23	41	45	53	64
10	25	36	43	51	60	26	40	46	53	64
11	27	41	47	53	64	28	43	50	55	64
Mean	20.55	35.82	41.09	48.00	60.45	22.45	39.09	45.27	52.27	63.00
σ	3.75	2.68	3.59	3.58	3.05	3.83	3.14	2.97	2.80	2.19

Table D-2. Maximum Legible Viewing Distances for Harbor-30 Turbidity Condition

Test Divers	Display Wavelength: 503 nm							
	4 mm Display Display Luminance (ft-L)				8 mm Display Display Luminance (ft-L)			
	.1	.3	1.0	10	.1	.3	1.0	10
1	--	--	--	--	--	--	--	--
2	12	13	15	18	12	14	17	18
3	13	14	15	18	16	17	17	20
4	13	11	12	16	12	12	14	17
5	--	--	--	--	--	--	--	--
6	8	9	11	14	9	10	14	15
7	8	10	12	16	8	10	12	16
8	13	13	15	18	12	16	18	20
9	9	10	10	15	9	12	12	16
10	9	10	13	16	13	13	14	17
11	12	13	15	17	13	14	16	17
Mean	10.78	11.44	13.11	16.44	11.56	13.11	14.89	17.33
σ	2.22	1.81	1.96	1.42	2.51	2.42	2.20	1.73

Table D-2. Maximum Legible Viewing Distances for Harbor-30 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 552 nm									
	4 mm Display Display Luminance (ft-L)					8 mm Display Display Luminance (ft-L)				
	.1	.3	1.0	10	30	.1	.3	1.0	10	30
1	--	--	--	--	--	--	--	--	--	--
2	8	10	13	17	19	10	12	15	19	20
3	10	12	15	19	20	12	15	18	19	21
4	6	8	11	14	17	10	13	15	16	18
5	--	--	--	--	--	--	--	--	--	--
6	6	10	12	16	17	7	11	13	17	19
7	9	10	9	15	18	8	10	14	16	19
8	9	11	12	18	19	9	13	15	20	21
9	7	10	12	16	18	8	11	13	18	18
10	6	9	12	17	18	9	11	14	18	19
11	9	11	14	17	19	12	13	15	18	19
Mean	7.78	10.11	12.22	16.56	18.33	9.44	12.11	14.67	17.89	19.33
σ	1.56	1.17	1.72	1.51	1.00	1.74	1.54	1.50	1.36	1.12

Table D-2. Maximum Legible Viewing Distances for Harbor-30 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 579 nm									
	4 mm Display Display Luminance (ft-L)					8 mm Display Display Luminance (ft-L)				
	.1	.3	1.0	10	30	.1	.3	1.0	10	30
1	--	--	--	--	--	--	--	--	--	--
2	5	10	13	18	18	8	10	13	19	20
3	8	11	13	18	20	9	14	16	19	21
4	6	9	11	16	30	8	10	13	17	20
5	--	--	--	--	--	--	--	--	--	--
6	6	9	12	16	18	7	10	12	17	19
7	8	10	13	15	18	8	12	14	17	19
8	7	9	12	17	19	8	12	14	19	21
9	7	10	10	16	18	8	11	13	17	19
10	6	10	12	17	19	8	12	14	18	19
11	8	10	14	17	20	9	12	14	19	21
Mean	6.78	9.78	12.22	16.67	20.00	8.11	11.44	13.67	18.00	19.89
σ	1.09	.67	1.20	1.00	3.84	.60	1.33	1.12	1.00	.93

Table D-2. Maximum Legible Viewing Distances for Harbor-30 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 590 nm									
	4 mm Display Display Luminance (ft-L)					8 mm Display Display Luminance (ft-L)				
	1	10	30	100	1000	1	10	30	100	1000
1	--	--	--	--	--	--	--	--	--	--
2	10	16	18	21	25	11	17	20	22	26
3	7	16	18	21	25	9	17	21	22	26
4	9	15	17	20	25	11	16	19	22	25
5	--	--	--	--	--	--	--	--	--	--
6	9	14	17	19	23	10	15	17	19	24
7	6	14	17	19	23	9	15	18	20	24
8	10	16	19	21	26	12	18	21	23	27
9	9	15	17	19	23	9	15	19	21	25
10	10	15	17	20	25	12	16	19	21	25
11	11	15	17	20	25	13	15	19	20	27
Mean	9.00	15.11	17.44	20.00	24.44	10.67	16.00	19.22	21.11	25.44
σ	1.58	.78	.73	.87	1.13	1.50	1.12	1.30	1.27	1.13

Table D-3. Maximum Legible Viewing Distances for Ocean-10 Turbidity Condition

Test Divers	Display Wavelength: 503 nm						
	4 mm Display				8 mm Display		
	Display Luminance (ft-L)				Display Luminance (ft-L)		
	.001	.003	.01	.03	.001	.003	.01
1	19	26	51	57	39	46	60
2	6	18	38	62	18	27	52
3	5	10	31	55	5	22	46
4	5	9	23	50	6	16	38
5	16	19	31	57	27	34	52
6	8	23	24	51	15	36	43
7	7	17	44	64	19	29	56
8	10	18	36	60	24	36	51
9	10	24	37	63	21	33	55
10	7	19	41	64	11	31	53
Mean	9.30	18.30	35.60	58.30	18.50	31.00	50.60
σ	4.72	5.50	8.69	5.17	10.20	8.26	6.54

Table D-3. Maximum Legible Viewing Distances for Ocean-10 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 552 nm				
	4 mm Display			8 mm Display	
	Display Luminance (ft-L)			Display Luminance (ft-L)	
	.003	.01	.03	.003	.01
1	5	19	59	19	49
2	6	27	57	12	51
3	5	36	58	19	49
4	9	24	40	21	36
5	14	36	56	29	50
6	14	29	57	28	45
7	5	40	51	20	60
8	14	27	43	30	43
9	6	23	46	26	50
10	12	39	60	24	55
Mean	9.00	30.00	52.70	22.80	48.80
σ	4.08	7.29	7.24	5.63	6.53

Table D-3. Maximum Legible Viewing Distances for Ocean-10 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 579 nm			
	4 mm Display		8mm Display	
	Display Luminance (ft-L)		Display Luminance (ft-L)	
	.01	.03	.003	.01
1	30	62	26	53
2	15	55	5	34
3	17	61	12	51
4	26	42	18	40
5	15	39	6	30
6	32	58	7	46
7	26	64	7	36
8	15	36	12	29
9	18	51	25	43
10	35	58	12	47
Mean	22.90	52.60	13.00	40.90
σ	7.78	10.16	7.64	8.49

Table D-3. Maximum Legible Viewing Distances for Ocean-10 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 590 nm						
	4 mm Display			8 mm Display			
	Display Luminance (ft-L)			Display Luminance (ft-L)			
	.01	.03	.1	.003	.01	.03	.1
1	6	23	56	24	38	47	64
2	6	16	41	6	16	26	60
3	5	12	42	5	11	33	64
4	8	19	40	5	17	32	47
5	5	21	45	7	15	34	64
6	5	16	44	5	9	36	54
7	5	22	52	5	7	34	64
8	7	16	40	7	11	32	55
9	6	7	39	7	15	27	61
10	5	9	38	7	13	30	54
Mean	5.80	16.10	43.70	7.80	15.20	33.10	58.70
σ	1.03	5.42	5.91	5.77	8.63	5.80	5.91

Table D-4. Maximum Legible Viewing Distances for Ocean-30 Turbidity Condition

Test Divers	Display Wavelength: 503 nm						
	4 mm Display Display Luminance (ft-L)				8 mm Display Display Luminance (ft-L)		
	.001	.003	.01	.03	.001	.003	.01
1	11	32	42	64	18	30	48
2	6	17	34	64	16	30	47
3	8	17	34	64	21	27	46
4	5	7	22	44	12	18	30
5	5	20	36	57	10	30	58
6	5	5	20	34	5	8	30
7	8	25	51	64	18	43	58
8	13	16	33	58	20	31	46
9	6	16	33	60	21	30	58
10	10	22	42	64	12	32	53
Mean	7.70	17.70	34.70	57.30	15.30	27.90	47.40
σ	2.83	7.92	9.18	10.28	5.36	9.23	10.43

Table D-4. Maximum Legible Viewing Distances for Ocean-30 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 552 nm				
	4 mm Display			8 mm Display	
	Display Luminance (ft-L)			Display Luminance (ft-L)	
	.003	.01	.03	.003	.01
1	5	20	64	28	51
2	8	32	64	23	50
3	10	32	64	22	49
4	8	19	40	20	43
5	16	38	53	32	54
6	5	36	48	7	44
7	17	52	64	37	58
8	15	32	59	22	42
9	5	16	45	16	54
10	19	43	64	17	59
Mean	10.80	32.00	56.50	22.40	50.40
σ	5.45	11.26	9.29	8.50	6.02

Table D-4. Maximum Legible Viewing Distances for Ocean-30 Turbidity Condition (Continued)

Test Divers	Display Wavelength: 579 nm			
	4 mm Display		8 mm Display	
	Display Luminance (ft-L)		Display Luminance (ft-L)	
	.01	.03	.003	.01
1	19	54	23	50
2	28	64	23	48
3	41	64	27	49
4	21	44	25	48
5	15	34	21	49
6	35	54	8	48
7	48	64	36	62
8	28	42	16	39
9	12	56	25	47
10	42	64	26	56
Mean	28.90	54.00	23.00	49.60
σ	12.30	10.79	7.30	5.99

Table D-4. Maximum Legible Viewing Distances for Ocean-30 Turbidity Condition (Continued)

Test Divers	Display Wavlength: 590 nm					
	4 mm Display			8 mm Display		
	Display Luminance (ft-L)			Display Luminance (ft-L)		
	.01	.03	.1	.003	.01	.03
1	11	18	50	12	29	39
2	5	25	52	5	5	40
3	5	22	52	5	26	39
4	10	33	62	10	22	46
5	8	23	54	5	18	36
6	5	18	56	5	14	36
7	5	24	62	12	12	49
8	8	22	40	7	13	30
9	5	6	35	5	17	26
10	13	34	62	8	21	51
Mean	7.50	22.50	52.50	7.40	17.70	39.20
σ	2.99	7.92	9.15	2.95	7.11	7.90